Integrated Flow and VOC Fate and Transport Modeling for the Original Landfill at the Rocky Flats Environmental Technology Site, Golden, Colorado

Technical Report

December 6, 2004

By

Integrated Hydro Systems, LLC

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Executive Summary

Development and results of integrated flow and Volatile Organic Compounds (VOC) fate and transport modeling to support the Original Landfill (OLF) Interim Measure/Interim Remedial Action (IM/IRA) document are described in this technical memorandum. The integrated hydrologic flow code MIKE SHE is used to simulate conditions that develop for closure configurations because system flows are complex, and realistic closure configuration model parameter values can be assigned in the physically-based code. Development of the integrated flow model follows an approach similar to that used in former Site-Wide Water Balance (SWWB) integrated flow modeling (KH, 2002), where saturated and unsaturated flows are dynamically coupled with overland and channel flows. Development of the fate and transport modeling follows the approach used in more recent modeling to support the Comprehensive Risk Assessment (KH, 2004) where a reactive transport code is used to simulate attenuation processes such as degradation, sorption, dispersion and diffusion.

The primary objective of the flow modeling involves simulating integrated flow conditions within the OLF for four closure configurations. In addition, the fate and transport of elevated levels of VOCs within the OLF are modeled to estimate a range of long-term groundwater concentrations at possible surface water discharge locations. The four OLF closure configurations considered include the following:

- Scenario 1 - IA reconfiguration, no OLF modifications;
- Scenario 2 - IA reconfiguration, OLF regrade (basecase);
- Scenario 3 - IA reconfiguration, OLF regrade, buttress fill, and drain;
- Scenario 4 - IA reconfiguration, OLF regrade, buttress fill, drain, and slurry wall.

These objectives are addressed in several steps. First, available geologic, hydrologic and chemical data, including recent water levels and geotechnical information, are compiled into a Graphical Information System (GIS) to conceptualize flow within the OLF. A localized, fully-integrated flow model is then developed for the OLF area based on these data for current conditions to demonstrate that parameter values are appropriate for simulating closure configurations. The integrated model is modified to simulate the hydrologic changes to the system for each of the four closure configurations. Finally, fate and transport of elevated levels of PCE and its daughter products are conservatively evaluated from inferred constant concentration source areas within the OLF using a reactive transport code.

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Current Configuration Data Evaluation

Several observations can be made from evaluation of available hydrologic data that are relevant to the geotechnical stability analysis:

1) Evaluation of historical groundwater level data in the OLF area indicates groundwater levels above the weathered bedrock range from 0 to 10 feet over about two thirds of the waste extent, while the levels are actually below the bedrock over the remaining one third.
2) For current conditions, average annual observed groundwater depths throughout the OLF area vary from over 20 feet depth at the top of the hillslope to less than 3 feet near Woman Creek and in shallow bedrock areas within the OLF.
3) Seasonal levels vary from 5 to 10 feet within the OLF.

Integrated Flow Model Development and Performance

The integrated flow model developed uses a much finer grid resolution of 25 feet than the former SWWB model to more accurately simulate the spatial variability of factors that affect flows in the OLF such as permeability distributions, surface topography and the weathered bedrock surface. The model only considers the Upper Hydrostratigraphic Unit (UHSU) material, but this unit is subdivided into four distinct layers that differentiate the OLF waste, fill material, native soils and the underlying weathered bedrock. Flow through the unsaturated zone is simulated using USGS mapped soils distributions and the current waste extent. Overland flow simulated in paved areas, or in unpaved areas when precipitation rates exceed the infiltration rate of the soils, is then routed into surface channels where it dynamically interacts with subsurface flows, or exits the model. The model also includes spatially distributed and time-varying inflow to channels from subsurface drains in the IA.

Results of model simulations for the current configuration using climate data from the year 2000 show that input parameter values reproduce average flow conditions well over the OLF. The model simulates average annual water levels within the OLF to within a foot of observed levels, and over the entire model area to within just over a foot with a standard deviation of less than four feet.

Closure Configuration Model Development and Simulation Results

Several model parameters are adjusted in the integrated flow model to simulate hydrologic effects of the closure configurations. In Scenario 1, adjustments are made to model input only in the IA. In the remaining scenarios adjustments are made to both the IA and OLF area. Closure modifications in the IA are similar to those assumed in the SWWB modeling (KH, 2002), where pavement and buildings are removed, subsurface drains are deactivated, and the surface of the

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IA is regraded and revegetated. For scenarios 2 through 4, the surface topography in the OLF is regraded using a surface that is only preliminary and will be modified based on this modeling and geotechnical analyses. In scenario 3, a structural buttress fill extending to the weathered bedrock surface and an upgradient drain are assumed along the southern extent of the OLF. In scenario 4, a slurry wall extending to the weathered bedrock surface is placed upgradient of the OLF to simulate hydrologic effects of reducing lateral inflow from the IA into the OLF.

A typical climate sequence, based on year 2000 data developed in the SWWB modeling (KH, 2002), is reasonable for simulating flow conditions within the model because this sequence reproduces time-averaged (10 years) water levels well in the current configuration model. To support geotechnical stability analyses, a wet-year climate sequence (based on 100 years) is simulated for Scenario 2 to approximate conservatively high groundwater levels that develop within the OLF area.

Modeling results can be summarized as follows:

1) Model results show that reconfiguring the IA (Scenario 1) causes groundwater levels to increase less than one foot over the OLF. However locally, levels decrease less than 3 feet and increase up to 4 feet. Simulated depths are similar to current conditions and range from less than 5 feet to over 20 feet within the OLF.

2) Simulated effects of regrading the OLF and reconfiguring the IA (Scenario 2) for a typical climate sequence (WY2000) cause levels to increase an average of about two feet. Locally they decrease up to 3.5 feet and increase up to nearly 7 feet. This is due in part to the adjustments in evapotranspiration caused by changes in the depth to groundwater below the new regrade. Simulated groundwater depths vary throughout the OLF, mostly in response to 'fill' and 'cut' adjustments. At the western and eastern waste extents depths increase to near 40 feet due to increased fill thickness. Saturated heights above the bedrock increase from 3 to 7 feet over most of the OLF compared to Scenario 1.

3) Simulating a wet-year climate (100-year basis) sequence for Scenario 2 causes average annual groundwater levels within the OLF to increase about two feet (ranging from 0 to 4 feet over the OLF) compared to those for a typical climate sequence. Results also indicate that groundwater reaches ground surface in shallow bedrock areas, though this could be controlled by increasing the regrade surface height above bedrock. These simulated groundwater levels represent conservatively high levels that might be sustained for up to a month during a wet year climate sequence.

4) Simulated effects of adding a buttress fill and upgradient buttress drain (Scenario 3) cause average annual groundwater levels to decrease less than

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one foot over the OLF. However locally, the drain causes levels to decrease up to 3 feet over the southern half of the OLF. Levels near the drain decrease about 11 feet. Simulated annual discharge rates from the drain are less than 1 gpm.

5) Simulated effects of adding a slurry wall to Scenario 3 (Scenario 4) cause average annual groundwater levels over the OLF to change less than one foot. However levels downgradient (south) of the slurry wall decrease less than 3 feet, while those upgradient of the slurry wall (north) increase up to 3 feet within about 300 feet.

6) Results of the current and closure simulations conducted in this study indicate that surface regrading results in the largest impact on OLF groundwater levels. Modeling also shows that seeps may occur under wetter climate though this could be controlled by adjusting the surface regrade topography.

7) A sensitivity analysis to determine the most sensitive parameters controlling water levels in the OLF was not conducted in this study, though results suggest that the regraded surface, bedrock depth and waste area hydraulic properties are the most sensitive. An uncertainty analysis to assess the range of hydrologic response to input parameter value uncertainty was also not conducted in this study. As such, simulated responses could change depending on the specific parameter values used, though reasonable values were assumed.

Fate and Transport Model Development and Simulation Results

Only tetrachloroethene (PCE) and its daughter products are evaluated in this study because they are detected in the OLF. Average annual groundwater velocity field estimated using the integrated flow model for Scenario 1 and 3 are used as the basis for reactive transport modeling using the RT3D code.

Reactive fate and transport modeling of PCE (and daughter products) detected in groundwater in the OLF waste indicate that concentrations at Woman Creek remain well below surface water standards for both Scenario 1 and 3. More conservative fate and transport scenarios (most conservative parameter values) show that groundwater concentrations may reach the buttress drain at detectable concentrations, though they remain below the surface water standards. Results of the fate and transport simulations assume that the PCE source concentrations remain constant during any regrade of the area.

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1.0 Introduction

Results of integrated flow modeling and VOC fate and transport associated with the Original Landfill (OLF) flow system are described in this technical memo in support of the OLF Interim Measure/Interim Remedial Action (IM/IRA). Key factors affecting the stability of the proposed OLF closure configuration are groundwater levels and their fluctuations with time. Although current groundwater level data in the OLF area are useful in assessing spatial characteristics such as groundwater depths, flow directions, and fluctuations in time, they should not be used to assess these characteristics for closure configurations. As groundwater flow at RFETS is complex, 3-dimensional and depends on many factors, an integrated flow model, using a similar approach to that described in the Site-Wide Water Balance Modeling report (KH, 2002), is developed to assess flow conditions under both current (WY2000) and closure configurations. The fate and transport of VOCs detected in the OLF are assessed using an approach similar to that described in a recent VOC fate and transport modeling report (KH, 2004).

The objectives of the modeling are described in Section 1.1. The steps taken to meet these objectives are outlined in Section 1.2. A brief discussion of available data and an analysis of these data are presented next in Section 2, followed by a description of the development of the integrated flow model and simulated results for current conditions in Section 3. In Section 4, specific closure scenarios are outlined, assumptions are outlined, and results are summarized. VOC fate and transport modeling is described in Section 5. Finally, key steps in this study are summarized and conclusions outlined in Section 6.

1.1 Objectives

The objectives of the modeling include the following:

1) Simulate integrated flow conditions within and surrounding the OLF waste for the following closure configurations:

- *No modifications to current OLF system;*
- *Regrade OLF area and IA closure;*
- *Regrade OLF area and IA closure, structural buttress fill downhill of waste, and upgradient drain; and*
- *Same as above, but includes a slurry wall upgradient of waste.*

2) Assess the following:

- Change in groundwater levels for each closure configuration from current conditions; and

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- Change in groundwater depths.

3) Assess the fate and transport of VOCs:

1.2 Approach

Several steps required to meet the objectives above are outlined graphically on Figure 1-1. The approach used here in developing the integrated model for the OLF system is similar to that described in (KH, 2002). Current system flows are first simulated to demonstrate that assumed model parameter values reproduce observed flow conditions adequately. Then several model input parameters are adjusted to simulate the integrated hydrologic system response of the closure configurations. The MIKE SHE code, developed by DHI (1999), is used to simulate the integrated flows at the OLF because it is physically-based (uses non-empirical flow equations) and fully-integrated, coupling subsurface flows (unsaturated and saturated zone) with surface flows (overland and channel flow). Effects of evapotranspiration and snowmelt are also considered in the OLF integrated flow model, and scenarios are continuously simulated using spatially-variable sub-hourly climate input over a full year.

A sensitivity analysis was not performed in this study. However, previous integrated modeling (KH, 2002, and KH, 2004) showed that the weathered bedrock surface, surface topography and hydraulic conductivity distribution are among the most important parameters. An uncertainty analysis to assess effects of input parameter uncertainty was also not conducted in this study, though reasonable values were assumed. As such, simulated responses presented could change depending on the specific parameter values assumed.

An important step in the development of the integrated flow model for the current configuration was updating the existing GIS database, developing new surfaces with recent data, and incorporating this information into the integrated flow model through a series of database algorithms.

2.0 Available Data and Analysis

The OLF study area, waste extent, and existing surface topography are shown on Figure 2-1. Vertical profile locations are also shown that correspond with the locations cited in Metcalf and Eddy (1995). The Building 444/440/460 area north of the OLF was included in the study to consider hydrologic impacts of the closure on the OLF area.

Available geologic, hydrologic, and chemical data in the OLF and surrounding area were reviewed and compiled into a spatial Geographical Information System (GIS) database to support model development. Most of this information was obtained from former SWWB modeling (KH, 2002), though several new datasets were prepared specific to the OLF. For example, a more accurate ground

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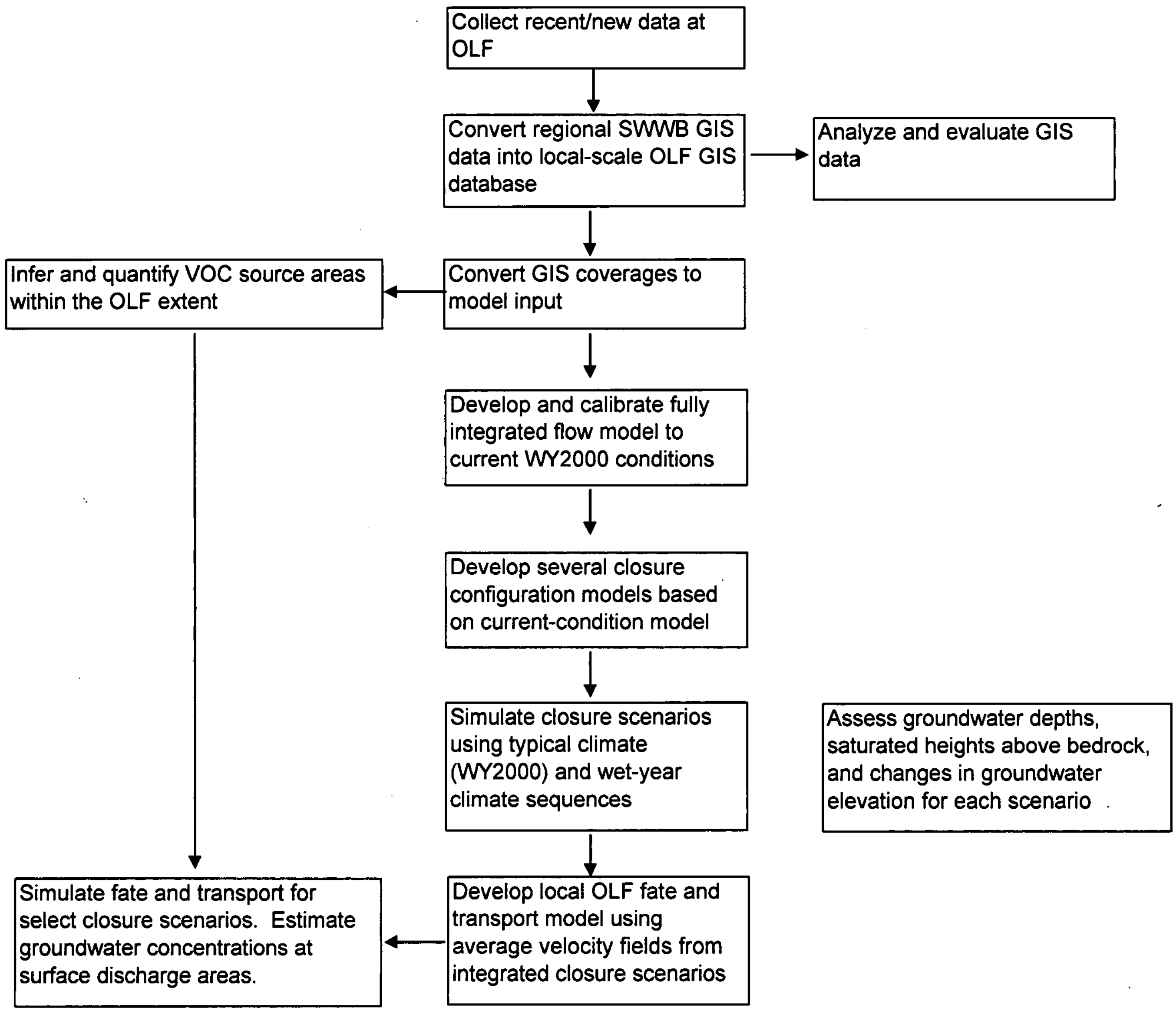

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Figure 1-1
OLF Modeling Approach

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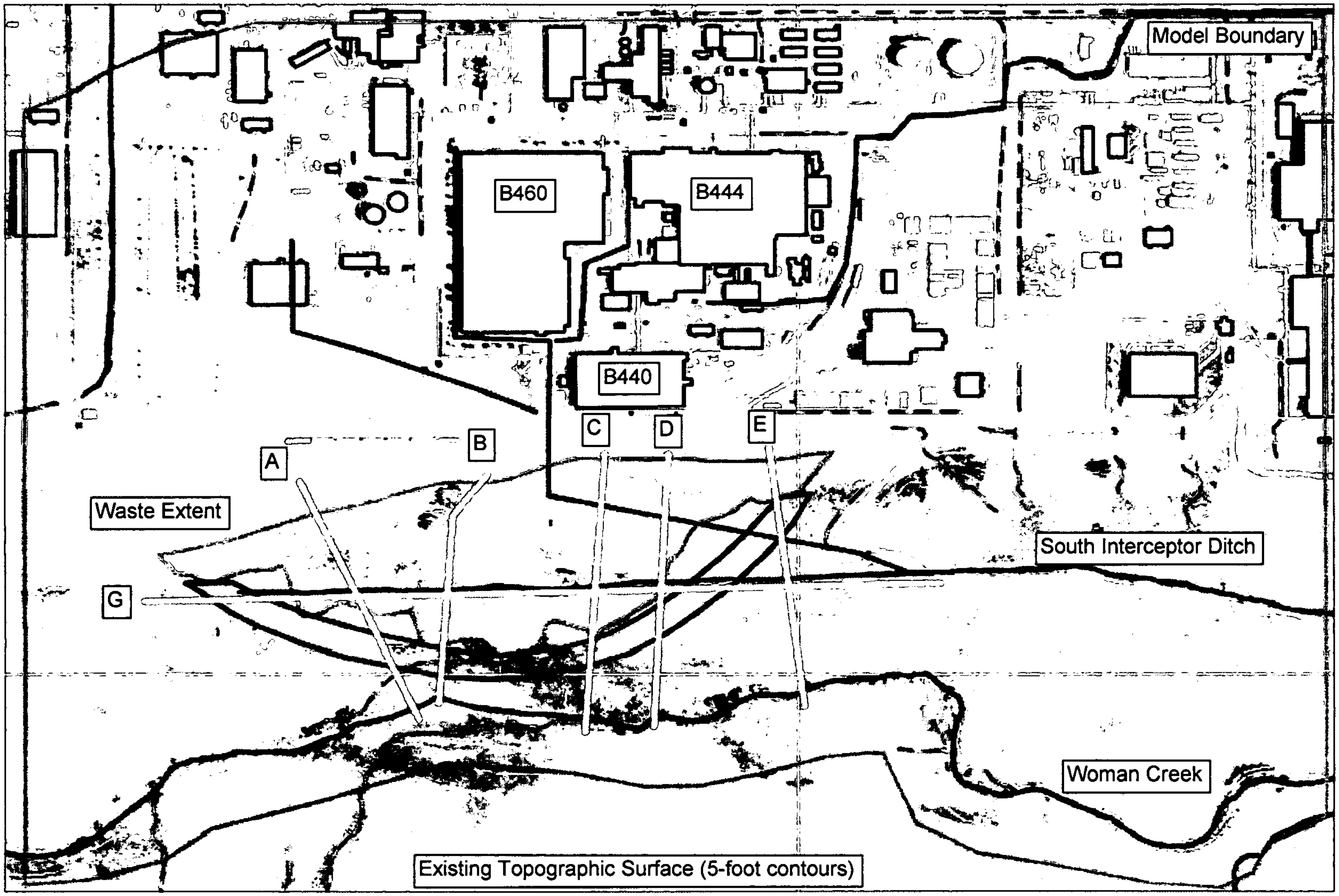

NOTE:

A Vertical Profile Location - Initially defined in Metcalf & Eddy Report (9/1995)

Figure 2-1
OLF study area, waste extent, current surface topography, and vertical profile locations.

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surface topography in the OLF area was obtained. In addition, all available field geologic borehole logs were reviewed to define approximate waste and bedrock surface contacts. Recent logs in the area, along with the higher resolution surface topography, were used to construct weathered and unweathered bedrock surfaces throughout the OLF area that are more accurate than previously approximated surfaces (KH, 2002). The refinement of the weathered bedrock surface is important as this was found to strongly control groundwater flow gradients and levels in hillslope areas.

Vertical profiles at lines shown on Figure 2-1 are illustrated on Figure 2-2. The existing topography, regrade surface, weathered bedrock, and unweathered bedrock are shown including approximate time-averaged groundwater levels determined through spatial interpolation. Thicknesses of unconsolidated material from the Building 440 area, south through the waste to Woman Creek, range from over 20 feet to less than 5 feet (Figure 2-3). Thickness of the waste material is also variable, ranging from less than 5 feet in the east-central area to more than 12 feet to the west. Unweathered bedrock thickness remains relatively uniform at about 20 feet through the OLF area.

More than 10 years of groundwater level data (Figure 2-4) in the OLF area, including recent 2004 data, were also reviewed and indicate several things. Groundwater levels in most wells within the OLF vary less than 5 feet annually, while surrounding, external, water levels typically vary between 5 to 10 feet over the year (some range from 10 to 15 feet per year, but are likely related to increased recharge from snow removal and mounding), reflecting seasonal recharge, evapotranspiration and drainage effects. The difference in magnitude of groundwater fluctuations between the two areas suggests that unsaturated and saturated zone hydraulic properties of the waste area may differ somewhat from non-waste areas.

Groundwater depths (Figure 2-5) in the Upper Hydrostratigraphic Unit (UHSU) decrease from about 20 to 30 feet below ground near the Building 440 area on the mesa to about 15 feet below ground within the waste, to less than about 5 feet below ground along Woman Creek. In Lower Hydrostratigraphic Unit (LHSU) wells in the OLF area groundwater depths are significantly lower than in nearby UHSU wells (57194, 71194 are greater than 100 feet, indicating that the LHSU and UHSU are hydraulically disconnected in the area.

Finally, a potentiometric surface map, constructed using time-averaged water level information, indicates a west-east groundwater divide just north of the Building 444. Therefore, groundwater south of this divide eventually flows towards Woman Creek.

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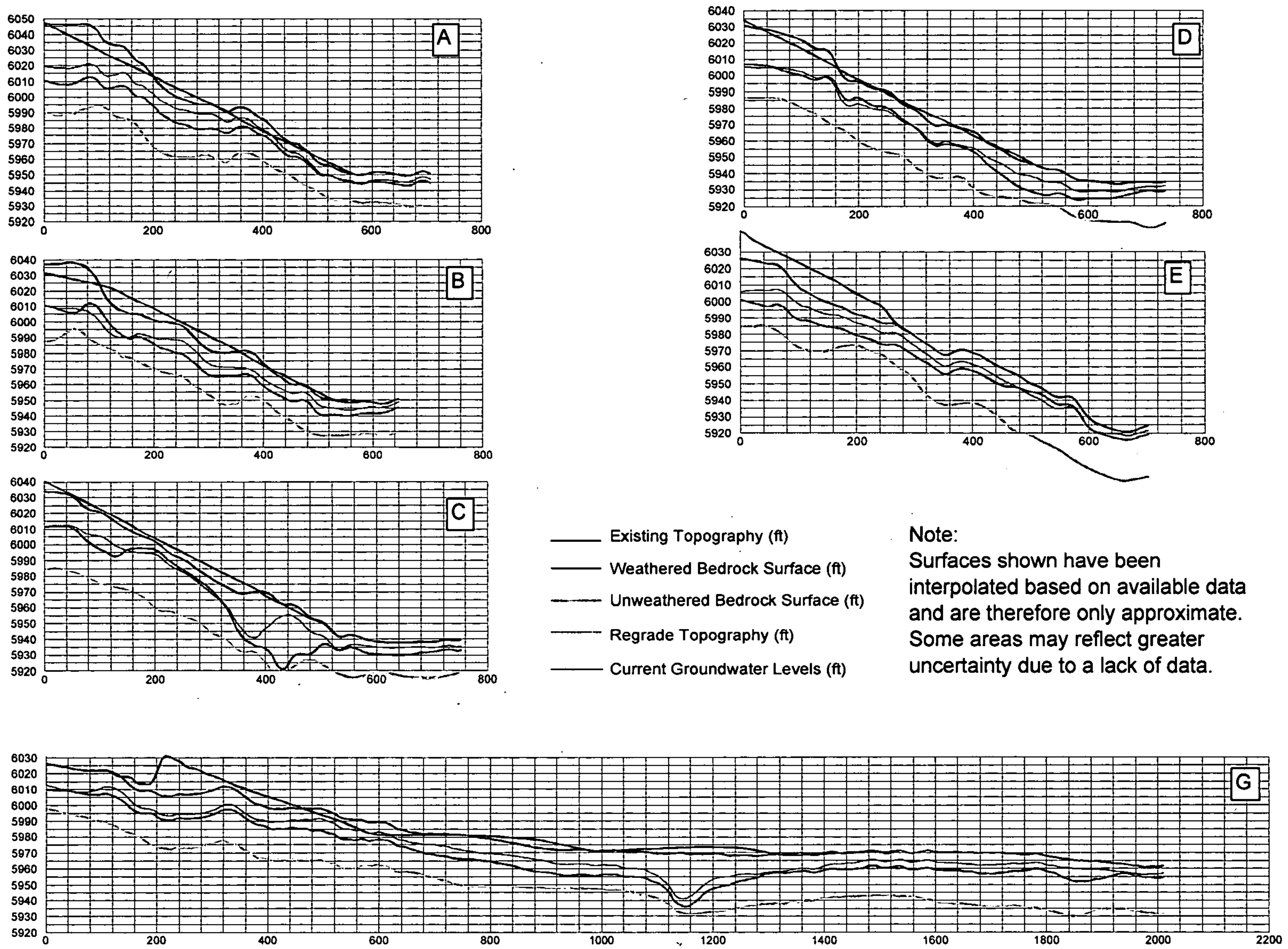

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Figure 2-2
Vertical profiles of hydrostratigraphy

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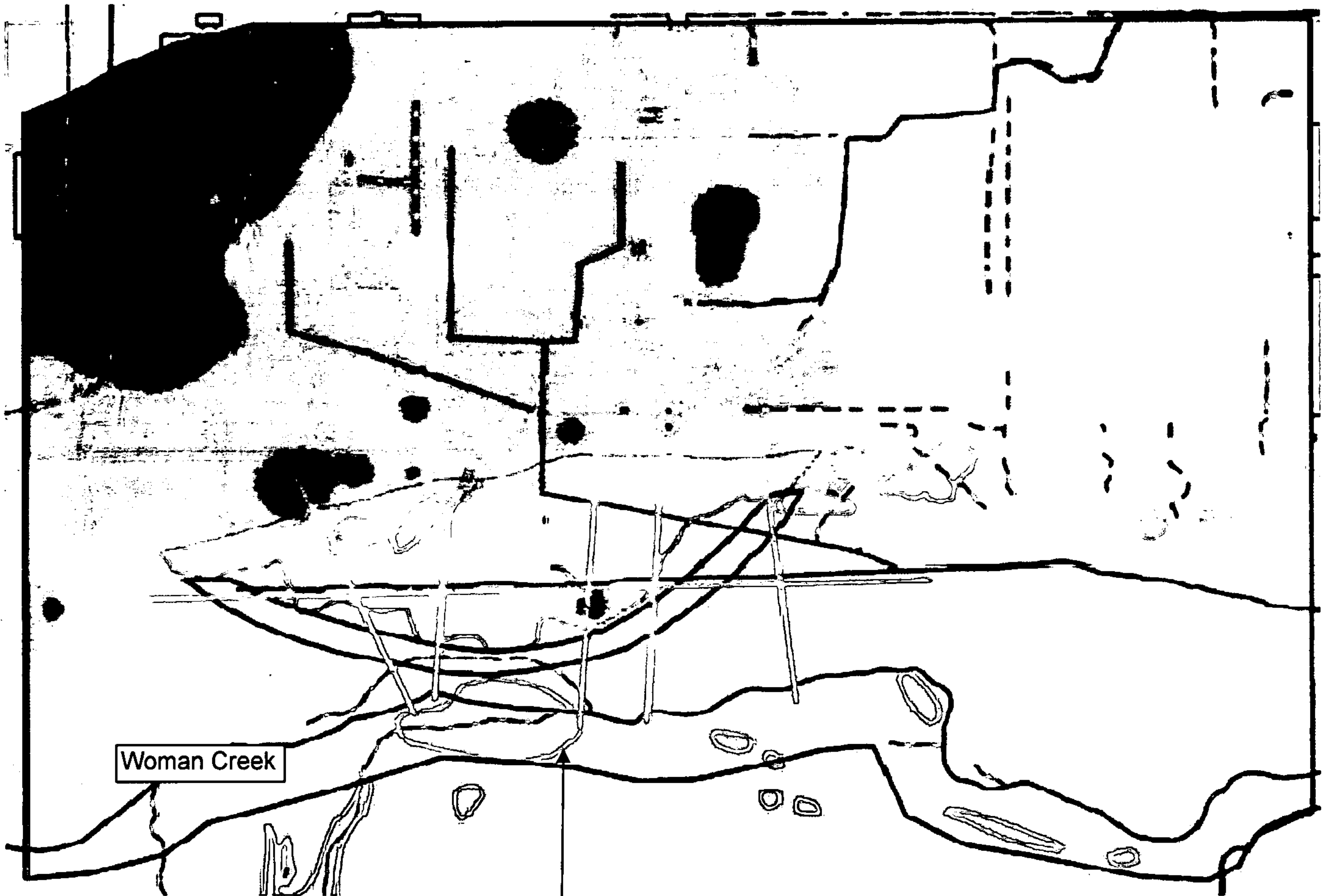

Unconsolidated Material Thickness (ft)

- <5
- 5 - 10
- 10 - 15
- 15 - 20
- 20 - 25
- 25 - 30
- >30
- No Data

Note:

1) Thickness over waste extent varies from 5 to > 30 feet.

2) Thickness generally decreases from northern waste area to the south.

3) Thin areas generally correlate with previously mapped seep areas.

USGS mapped seep areas. Most are not active during typical year climate sequences.

Figure 2-3
Approximate thickness of unconsolidated material (depth to weathered bedrock), (ft).

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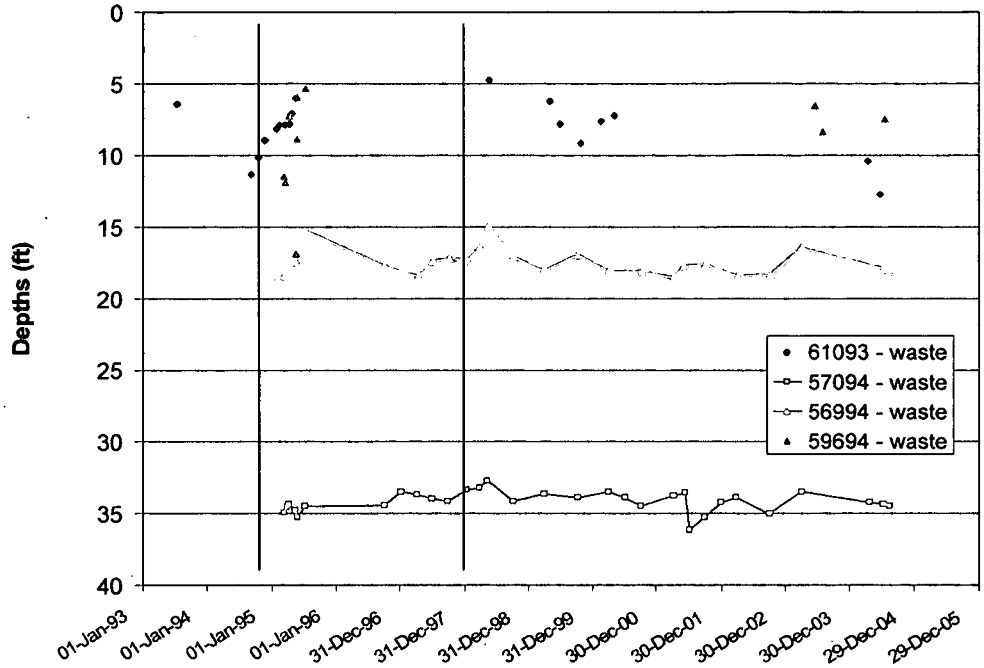
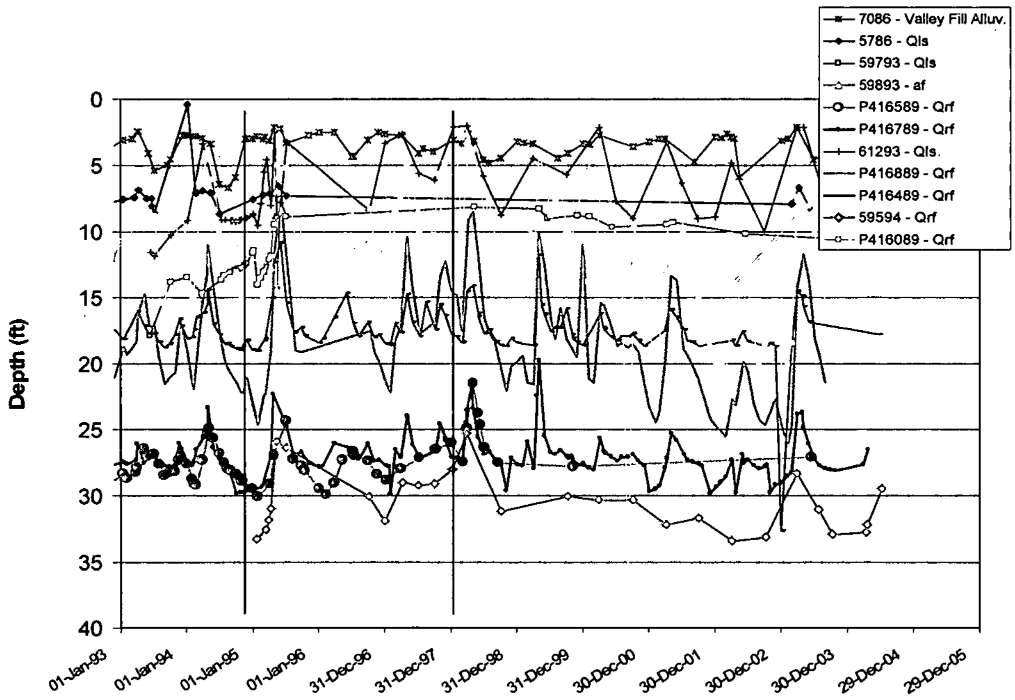


Waste area groundwater depths (ft)



Non-Waste area groundwater depths (ft)

Figure 2-4
Waste area and non-waste area groundwater depths with time (feet)

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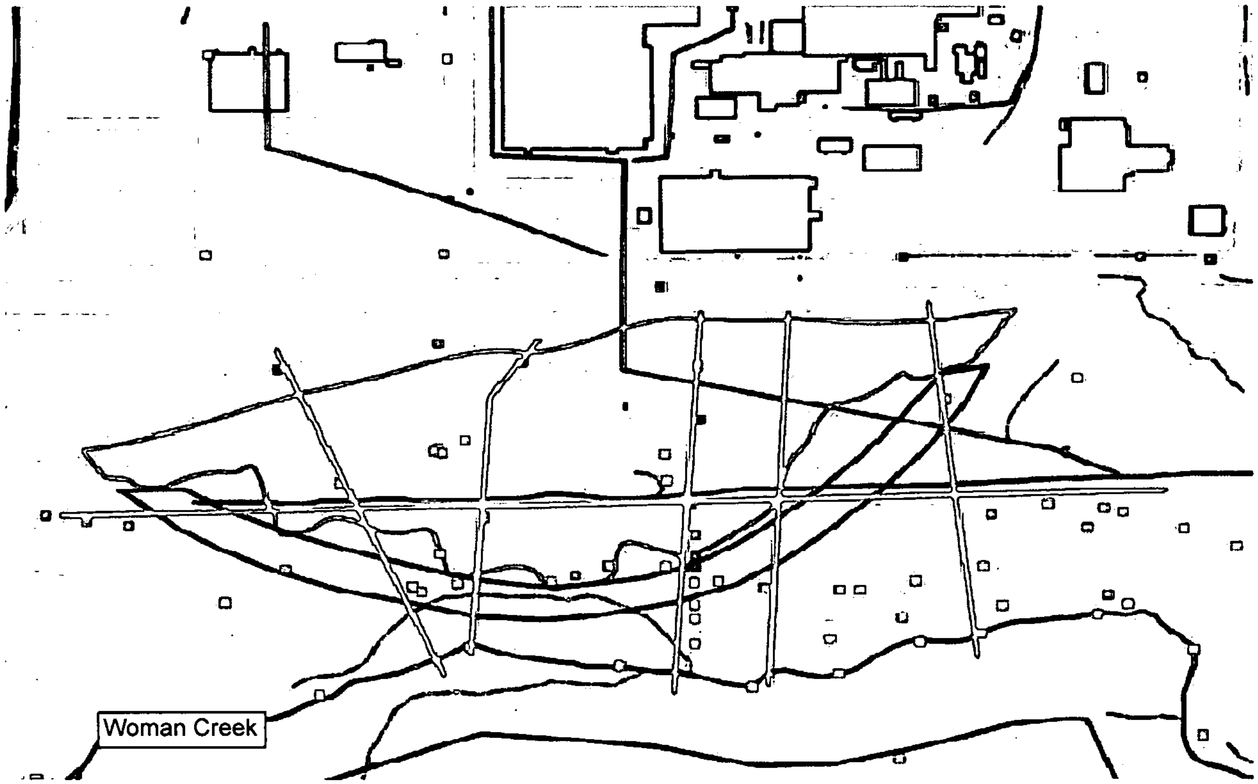

Time-averaged Groundwater Depths (ft) below ground surface at well locations

	1 - 5
	5 - 10
	10 - 20
	20 - 30
	30 - 99.296

Note:

1) Several locations shown along Woman Creek are control points used in defining initial conditions for the integrated flow model and are not wells.

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Figure 2-5
Time-averaged groundwater depths in OLF study area

3.0 Integrated Model Development and Performance for Current Conditions

3.1 Integrated Model Development

Constructing the integrated flow model involved several steps. First, the integrated flow model is based on a 25-foot numerical grid, as shown on Figure 3-1, to better simulate local flow conditions associated with the OLF (the SWWB model used a 200-foot grid resolution). Several GIS techniques were used to convert spatial hydrogeologic GIS information onto the finer grid. Spreadsheet algorithms were then used to convert gridded GIS information into model input. Figure 3-2 shows modeled utility corridors and drain distributions and Figure 3-3 shows modeled vegetation and unconsolidated soil distributions in the OLF area. These are examples of OLF GIS coverages converted into model input.

The saturated portion of the model is specified using four layers, the upper two for unconsolidated materials and drains, and the lower two for weathered bedrock. At each model cell, an unsaturated zone column is discretized into more than 100 cells to describe the non-linear dynamics including infiltration, depth-varying evapotranspiration, redistribution, and eventually groundwater recharge (using a full Richard's based equation). Overland flow and channel flow are simulated like in the SWWB modeling. Unsaturated and saturated zone hydraulic properties determined through integrated model calibration conducted for the original SWWB model and subsequent VOC fate and transport modeling (KH, 2004) were specified in the OLF model. However, new values for drain conductances and hydraulic properties for the waste were determined through initial OLF model simulations.

3.2 Model Performance – Current Conditions

The integrated model of the current system configuration, using climate data from October 1999 through September 2000, reproduced observed flow conditions well. Model simulations require that the WY2000 climate sequence is cycled for three consecutive years to stabilize effects of prescribed initial conditions. Model performance is assessed by comparing time-averaged simulated and observed water levels at wells throughout the model area (Figure 3-4). Results indicate that the model simulated time-averaged heads are within 3 feet in most locations. This is considered good given the complexity of flows in the area and change in topographic relief over the model area. Furthermore, residuals appear to decrease to within 3 feet from the upper waste area to Woman Creek. In some areas, levels are over-estimated between 3 to 7 feet. This discrepancy can be explained by an underestimation of drain discharge in the area, increased localized recharge due to runoff from paved areas into unpaved areas, or the reduced groundwater discharge to channels. These factors become unimportant in closure configurations.

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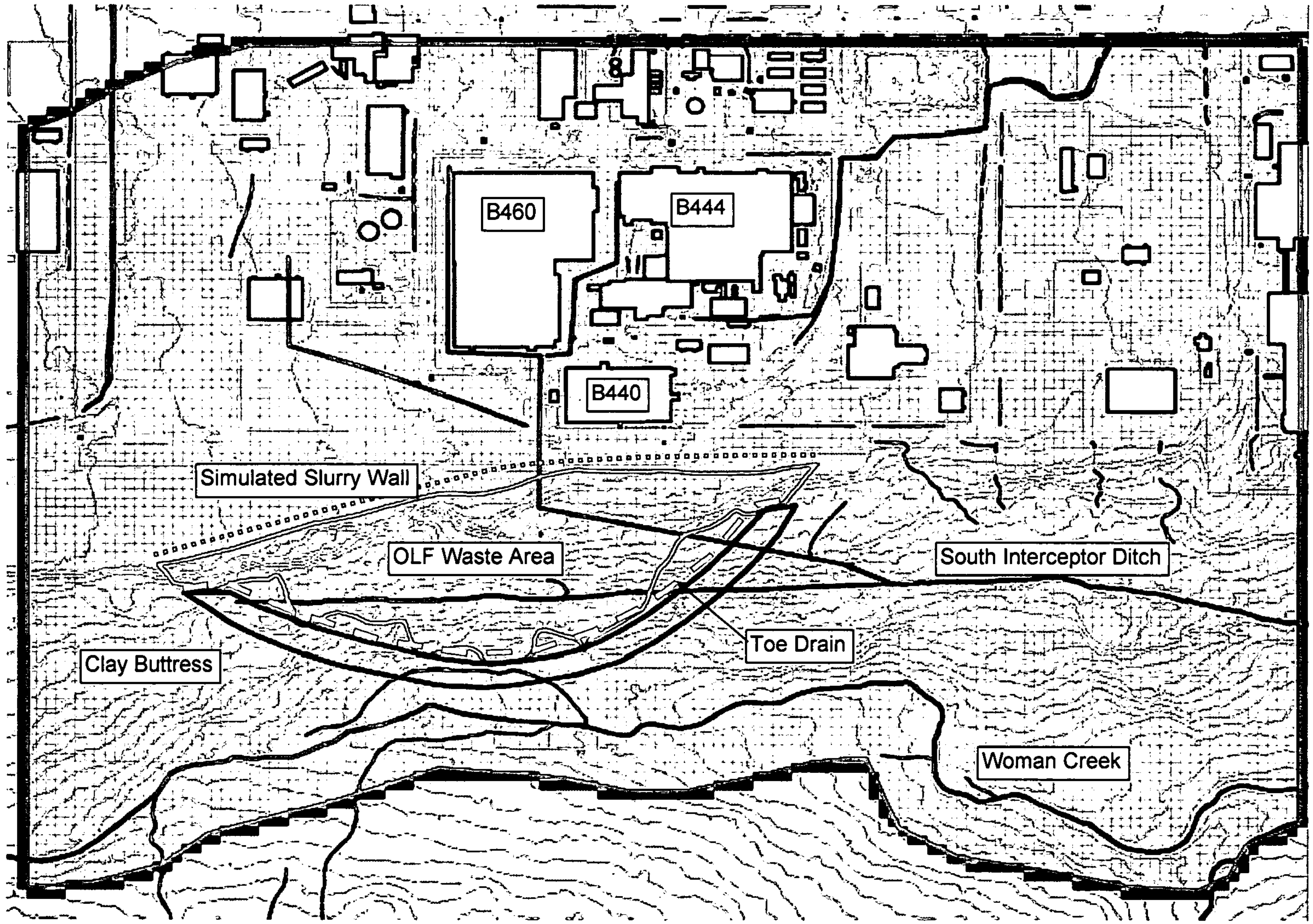

Note:
1) MIKE SHE grid spacing is 25 feet.
2) Slurry wall, Buttress Fill and Drain only shown here for reference (only occur in closure configuration).

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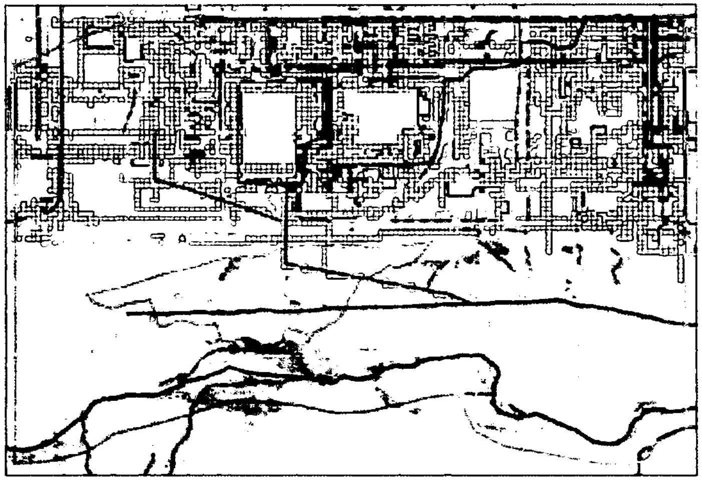
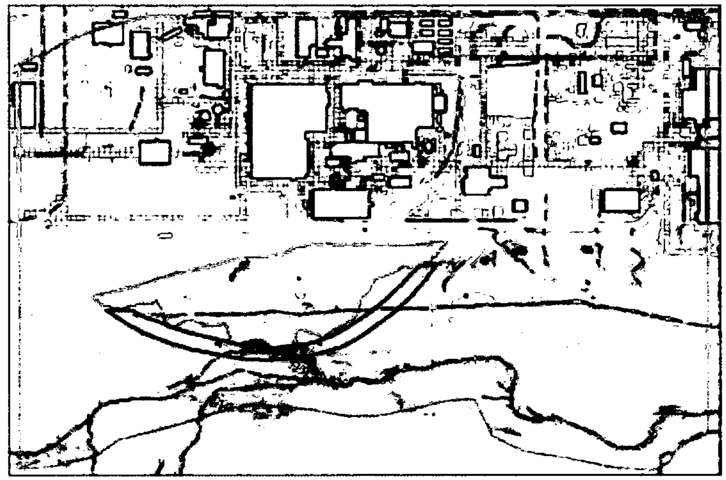
Figure 3-1
Integrated Flow Model Grid and Boundary



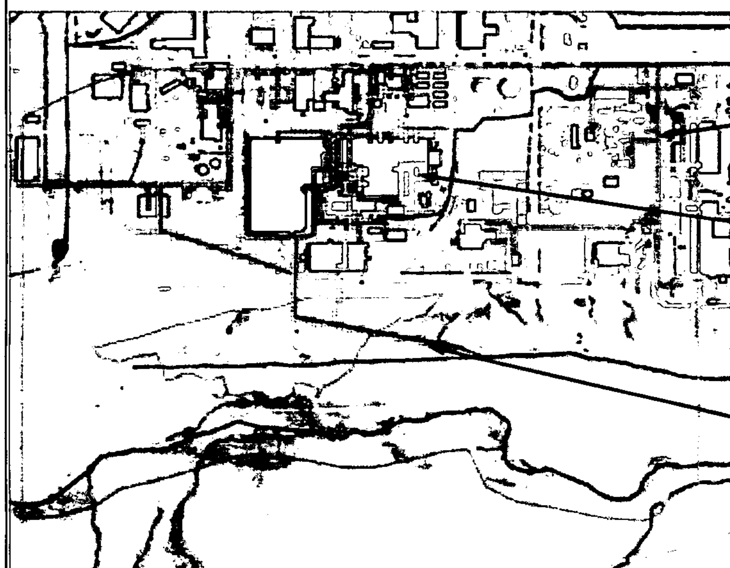
Subsurface Utility Corridors

(Preferential Pathways)



Water Supply Lines

(Aquifer Recharge)



Note:
1) Color variation shown on two upper plots reflect density of utility corridors or water supply lines within each model cell (25 feet dimension). Darker colors indicate greater densities.

Figure3-2
Simulated Utility Corridors and Subsurface Drains

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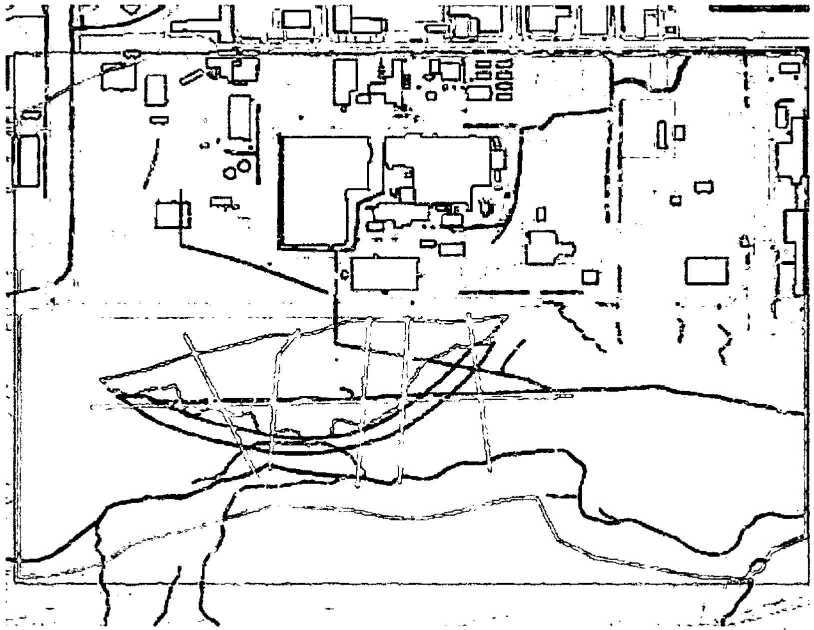
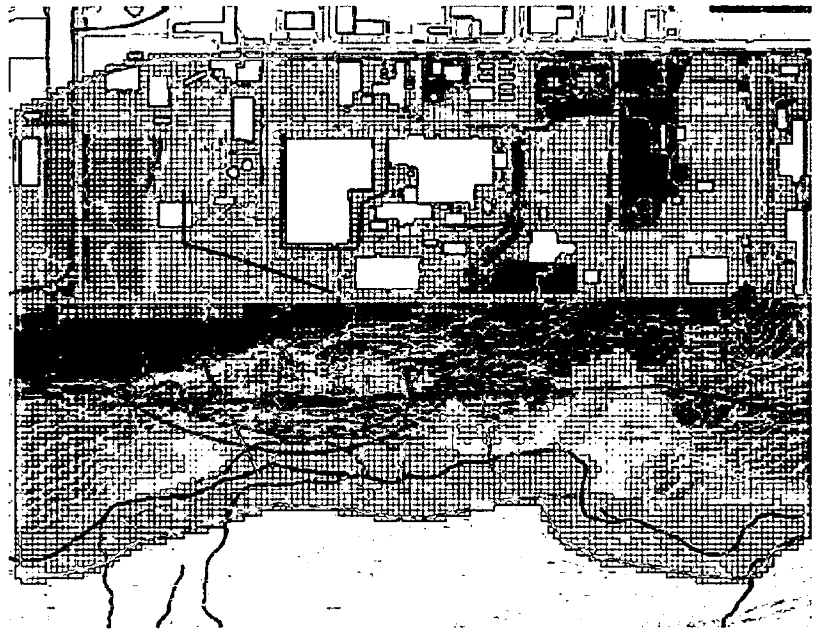


Vegetation Distributions



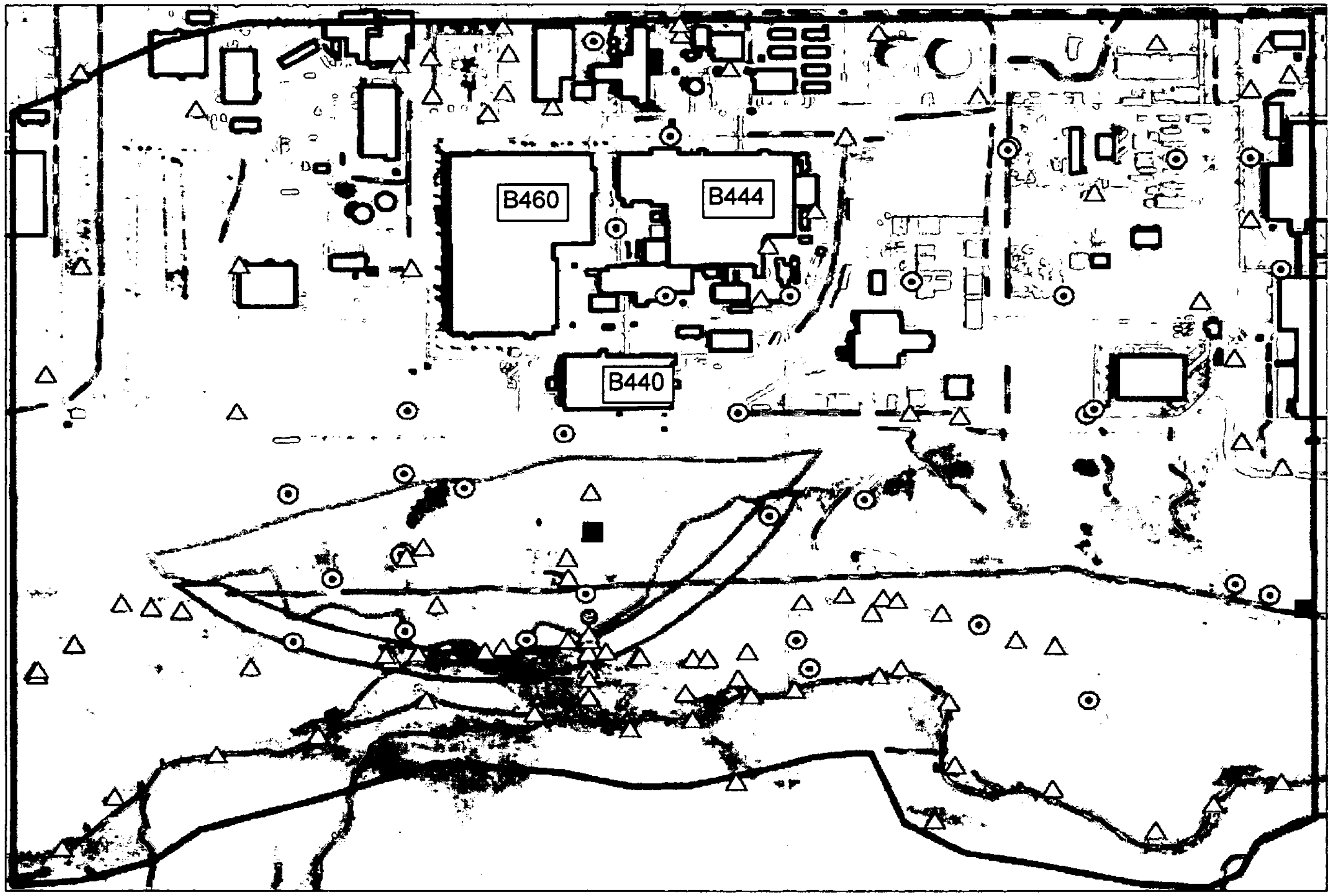
Unconsolidated Soil Distributions

NOTE:
1) Colors represent major vegetation zones
2) Six major vegetation zones defined
   - -mesic
   - -xeric
   - -riparian
   - -wetland
   - -paved areas (only surface evaporation-interception)
   - -dirt areas (only evaporation)

NOTE:
1) Twenty-eight soil zones defined to simulate flow through the unsaturated zone.
2) Major distribution defined by USGS surficial material definitions (i.e., Qrf, Qls, Qp, Qc, Qt, Qp, and Qls),
3) Within major distributions, soil types further subdivided based on depth to bedrock (5-foot depth increments).

General Note:
1) The vegetation and unconsolidated soil distributions are only shown here to indicate the resolution and spatial variability included in the integrated flow model. Refer to the SWWB modeling report for more detailed description based on field mapping (KH, 2002).

Figure 3-3
Model Input -
Soil and Vegetation Distributions



Simulated minus observed groundwater depths (feet).

	< -3
	-15 - -10
	-10 - -4
	-4 - 4
	4 - 10
	10 - 15
	> 3

Note:

1) Negative (red) difference denotes model under-simulates groundwater levels.

2) Positive (blue) denotes model over-simulates groundwater levels.

Figure 3-4.
Difference between simulated and observed time-averaged groundwater depths

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Simulated annual surface flow at gage GS22, though less than observed indicates most surface events are captured in peak flow, timing of events, snowmelt, and baseflow. Additional adjustment of drain conductances would likely improve the comparison between observed and simulated surface flows. However, the drain conductances are unimportant in evaluating impacts of closure configurations on system flows as the drains are removed in these simulations.

Figure 3-5 and 3-6 show the simulated annual average groundwater depths based on the existing topography and the simulated average annual saturated heights above the weathered bedrock surface, respectively. Simulated depths are quite variable over the OLF model area. Depths range from 7 to 10 feet north of Building 440/444/460 area to greater than 20 feet at the top of the slope and then decrease to 3 to 7 feet near Woman Creek. Saturated heights above the weathered bedrock, important to the stability analysis in the waste area, only range from 5 to 10 feet in the west-central area, and are actually unsaturated in the east-central area.

4.0 Closure Configuration Integrated Flow Model Development and Simulation Results

4.1 Closure Configuration Scenarios

Changes to the integrated hydrologic flow regime at and surrounding the OLF were evaluated for several different closure configurations. For each of the closure configurations, it is assumed that the configuration in the Industrial Area (IA) (north of the OLF) undergoes modifications consistent with those described previously in both the SWWB modeling (KH, 2002) and more recent VOC fate and transport modeling (KH, 2004). The only differences in the IA closure configuration from these previous evaluations are the surface topography and drainage. These were updated during August 2004 and are used in this analysis. Major assumptions in the IA closure configuration are briefly summarized below. Specific OLF-related changes are described next for each scenario.

***Key IA Closure Configuration Assumptions include the following*:**

- Buildings are removed, but basements for B444 are assumed to remain;
- Pavement removed;
- Sanitary, storm and footing drains deactivated;
- Leaky water supply lines deactivated;
- Surface topography regrade (over IA); and
- Surface drainage modifications.

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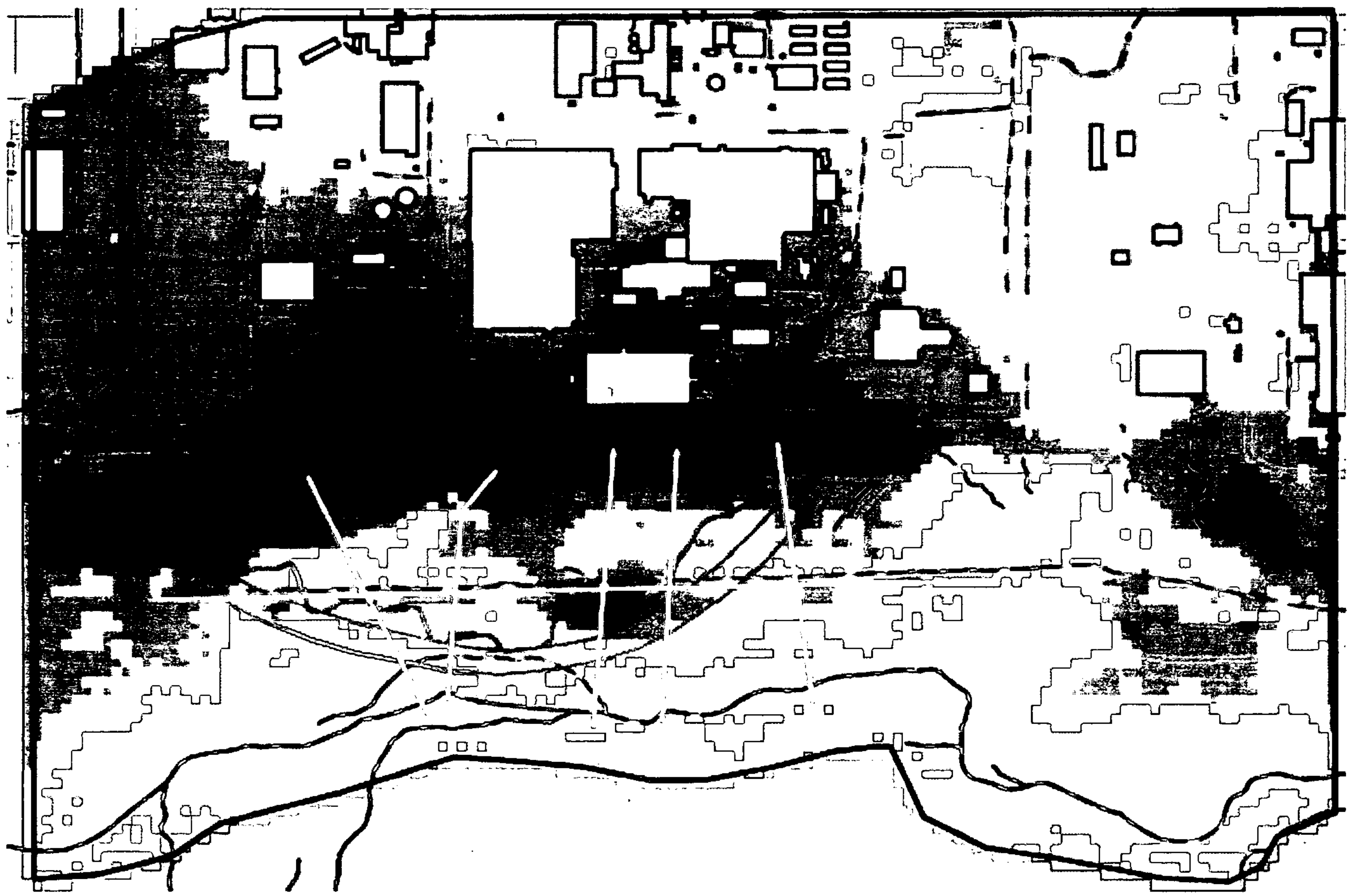

Note:
1) Negative numbers (yellow) indicate groundwater levels are above ground surface. These areas represent seeps or baseflow.

2) Average annual levels are calculated from simulated levels calculated every 6 hours over WY2000 (October 1999 to 2000).

Figure 3-5
Current Conditions - Simulated (Typical Climate) average annual groundwater depths (ft)

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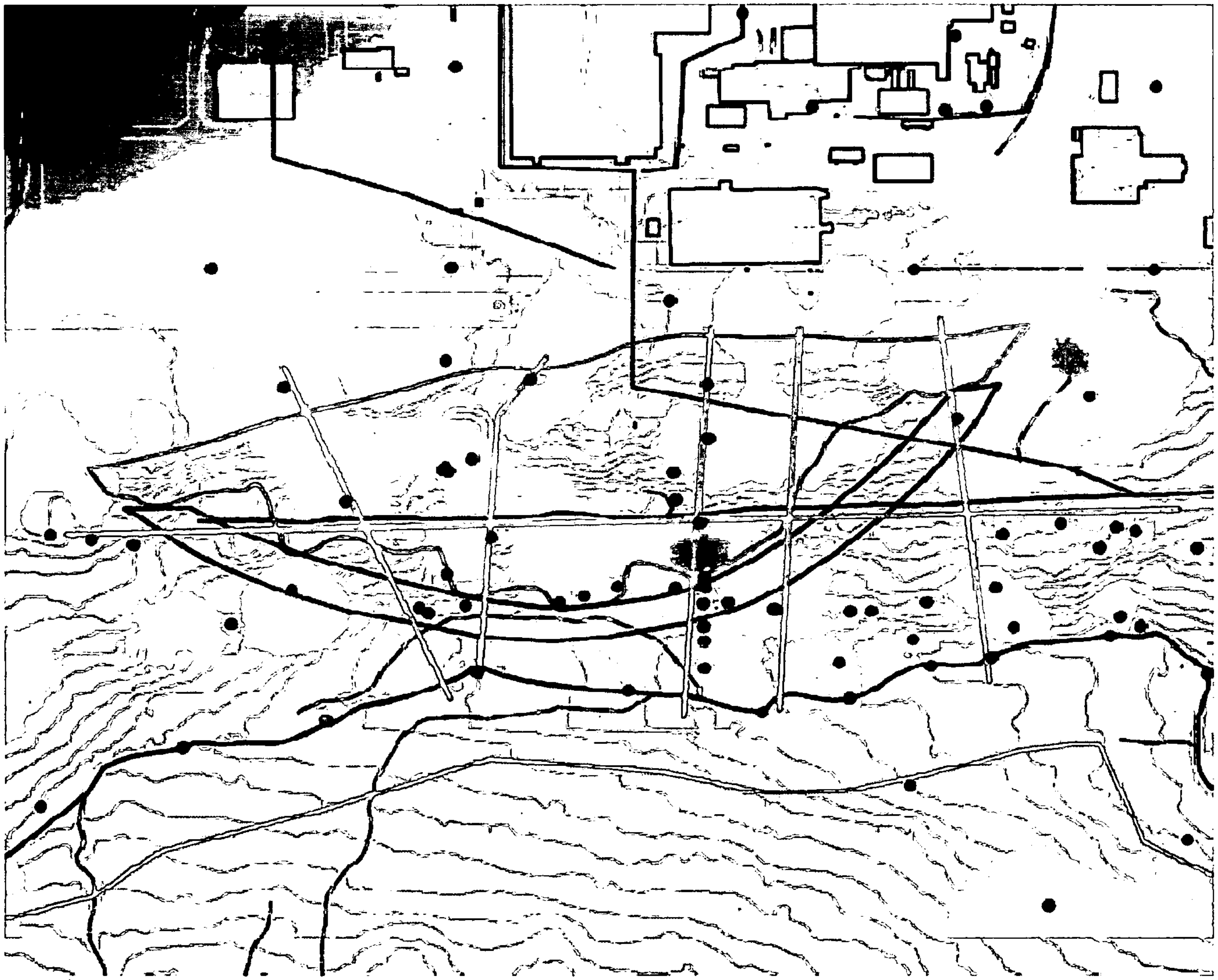

Calculated average annual groundwater height above weathered bedrock (feet).

-15 - -10
-10 - -5
-5 - 0
0 - 5
5 - 10
10 - 15
15 - 20
20 - 40
No Data

Note.

1) Saturated heights calculated by subtracting simulated average-annual groundwater levels from the weathered bedrock surface.

2) Negative numbers indicate areas where groundwater levels are below weathered bedrock.

3) Positive numbers indicate saturated groundwater heights above the top of the weathered bedrock surface.

Figure 3-6
Current Conditions - Simulated (Typical Climate) average annual saturated height above Weathered Bedrock surface (ft).

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Scenario-specific Closure Configurations and Assumptions include the following:

- **Scenario 1 – IA Regrade-only**
  - IA undergoes closure configuration (as per above);
  - No changes made to existing OLF area; and
  - Typical climate year sequence assumed (WY2000).
- **Scenario 2 – IA & OLF Regrade (basecase)**
  - IA undergoes closure configuration (as per above);
  - OLF area is regraded;
  - OLF area is re-vegetated;
  - Fill material is used as part of regrade (assume Qrf); and
  - Typical and Wet Year (100-year basis) climate year sequence assumed.
- **Scenario 3 – IA & OLF Regrade, Buttress fill, Buttress drain**
  - Same as Scenario 2;
  - Includes Buttress fill and Buttress drain on Upgradient side; and
  - Typical climate year sequence assumed (WY2000)
- **Scenario 4 – IA & OLF Regrade, Buttress fill, Buttress drain, and Slurry Wall**
  - Same as Scenario 3, but includes slurry wall immediately north of the waste area footprint.

In the 'basecase' OLF closure configuration scenario (Scenario 2), both the IA and OLF are reconfigured. To the north of the OLF, the IA is closed as described in the VOC Fate and Transport integrated modeling (KH, 2004). Pavement, buildings, drains and water supply lines are removed, the IA is regraded, and then re-vegetated. Over the OLF area, only the ground surface is regraded and re-vegetated.

Three-dimensional perspective views of the current, regrade, and weathered bedrock surfaces are shown on Figure 4-1a. The change in surface topography and unconsolidated material thickness is shown on Figure 4-1b. Two notable changes occur in the OLF area that cause notable changes in local hydrologic flow conditions. First, the regrade results in increases in unconsolidated thickness up to 30 feet, and decreases up to 20 feet. This in turn increases and decreases the depth to the weathered bedrock from the new regrade. These changes cause groundwater level adjustments throughout the waste area described further in Section 4.2.

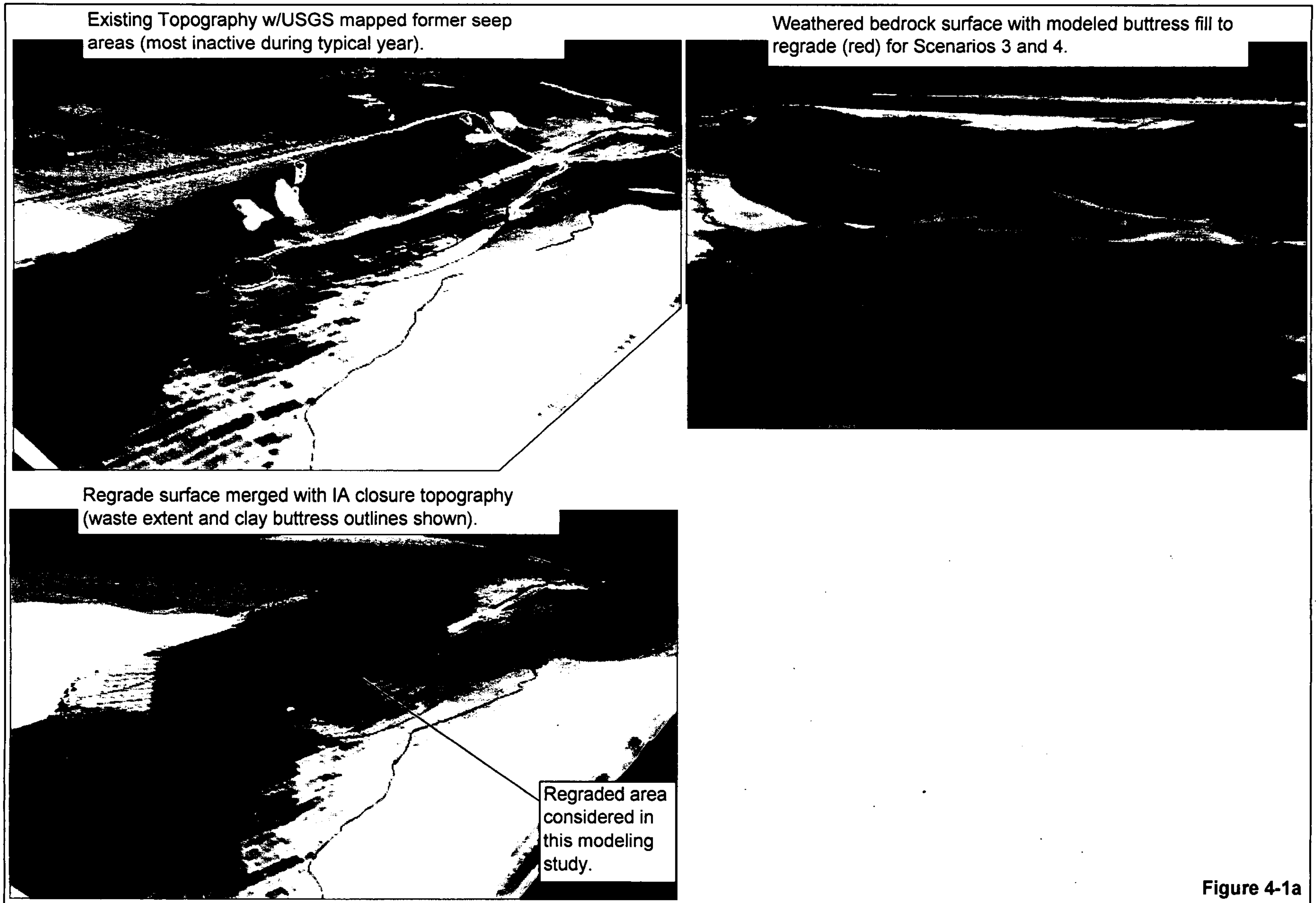

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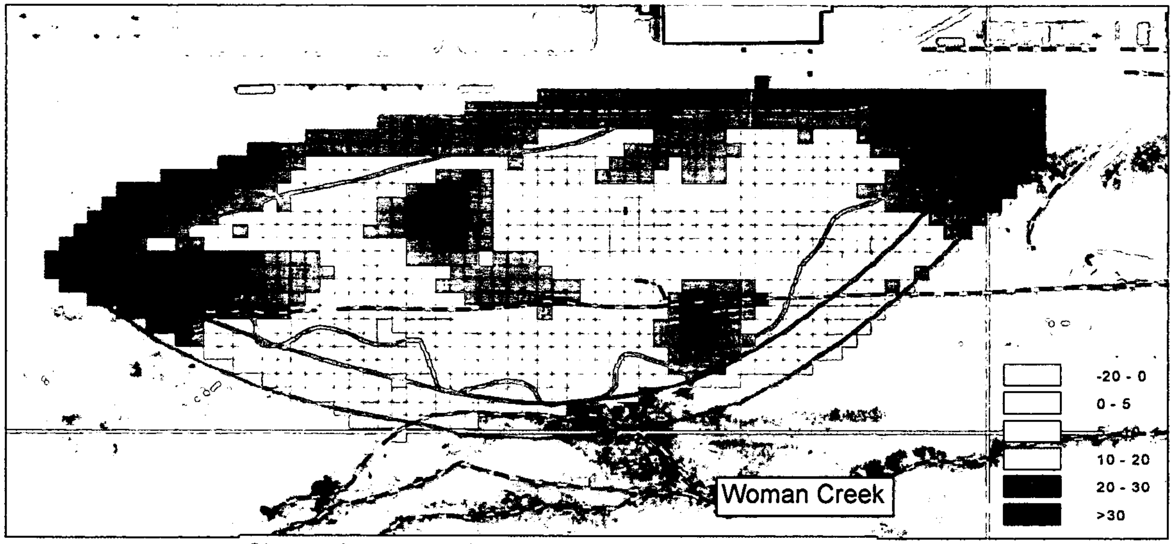
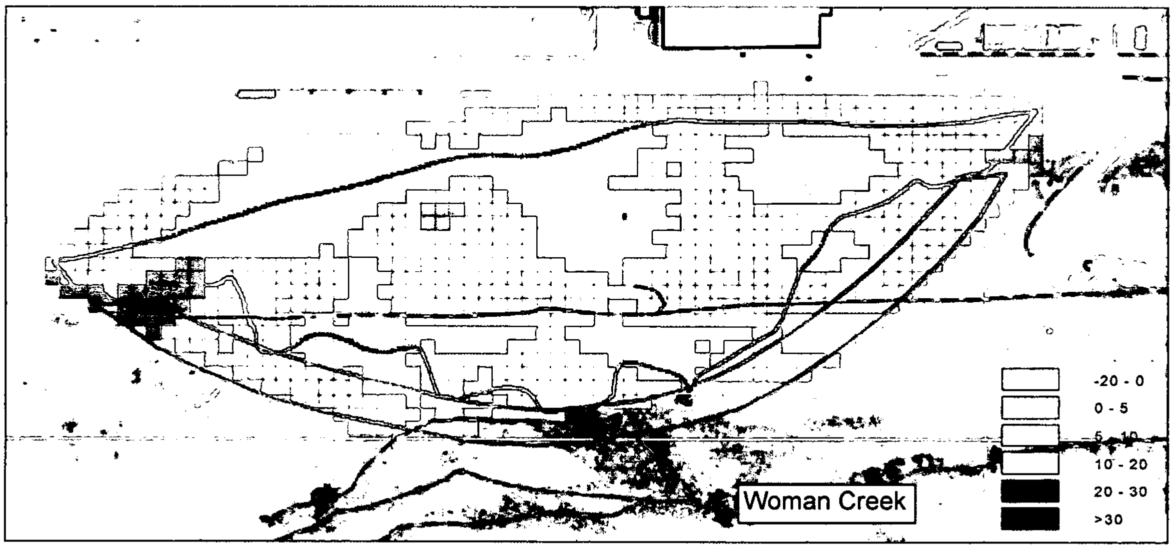
Figure 4-1a
Current, regrade and bedrock surface 3-dimensional perspective views



Change in unconsolidated thickness due to regrade (ft).



Change in surface topography (Regrade surface minus existing surface).

Note:

1) Thicknesses shown in feet.

2) Change in surface topography results in greater fill areas and volume than cut areas.

3) Positive numbers indicate increase in thickness. Negative numbers indicate a decrease in thickness.

Figure 4-1b
Change in OLF surface topography and unconsolidated thickness.

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4.2 Simulation Results - Closure Configurations

Results of model simulations are summarized in this section. Simulated groundwater depths below surface topography are plotted for each scenario to assess possible seep development. Plots of simulated water levels above the top of the weathered bedrock are used in the geotechnical slope stability analysis. Finally the change in water levels between different scenarios is shown to demonstrate the relative effects of each scenario's modification on the OLF hydrologic conditions.

4.2.1 Scenario 1 – No OLF Regrade

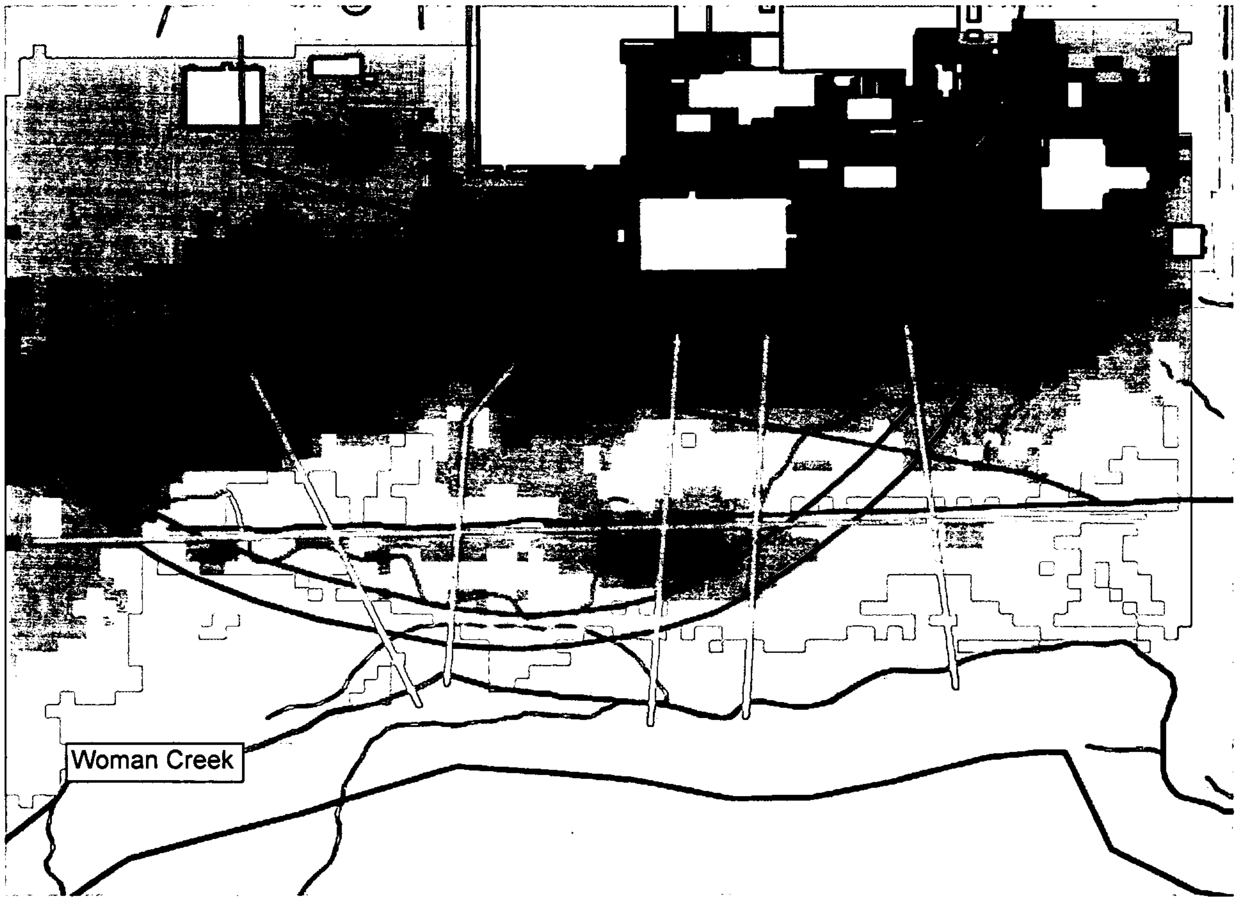
This scenario was simulated to assess hydrologic effects over the OLF area due to only IA reconfiguration. Figure 4-2 shows simulated average annual groundwater depths over the OLF area. A reduced model area was utilized to improve computational efficiencies. The range of simulated depths are similar to those calculated for current conditions and range from less than 3 feet in the west model area to more than 23 feet in the northern waste and south-central area. Average annual simulated saturated heights above weathered bedrock (Figure 4-3a) are similar to current conditions, but increase slightly in the western area (from <1 to 15 feet).

The change in groundwater levels from current conditions (Figure 4-3b), which reflects the relative effect of the IA reconfiguration, indicates levels increase less than a foot on average over the OLF. Locally, levels decrease less than 2.5 feet and increase up to 4 feet. The average increase is caused by a combination of factors, but is mostly due to removal of footing drains and removal of impervious areas.

4.2.2 Scenario 2 – OLF Regrade

A number of figures were generated to illustrate how the OLF area responds to the combination of IA closure (Scenario 1) and only a regrade in the OLF area. Simulated average annual depths for the OLF regrade show changes that mostly reflect the adjustment in unconsolidated material thicknesses (i.e., see Figure 4-1). As shown on Figure 4-4, depths increase in areas where the existing topographic surface is 'filled', while depths tend to decrease relative to the new surface topography, in areas where the existing surface is 'cut'. The range of depths is similar to that which develops in Scenario 1, and also do not indicate seep discharge, though levels are within 3 feet of surface.

An annual water balance evaluation of only the OLF waste extent (as shown on Figure 3-1), summarized on Figure 4-5) indicates that most precipitation



Simulated average annual groundwater depths (feet).

	-10 - 0
	0 - 5
	5 - 10
	10 - 15
	15 - 20
	20 - 45

Note:

1) Scenario 1 assumes no modifications to the OLF, but IA is closed per site configuration.

2) Negative numbers (yellow) indicate groundwater levels are above ground surface. These areas represent seeps.

3) Scenario 1 assumes no modifications to the OLF.

Figure 4-2
Scenario 1 - Simulated (Typical Climate) average annual groundwater depths (ft)

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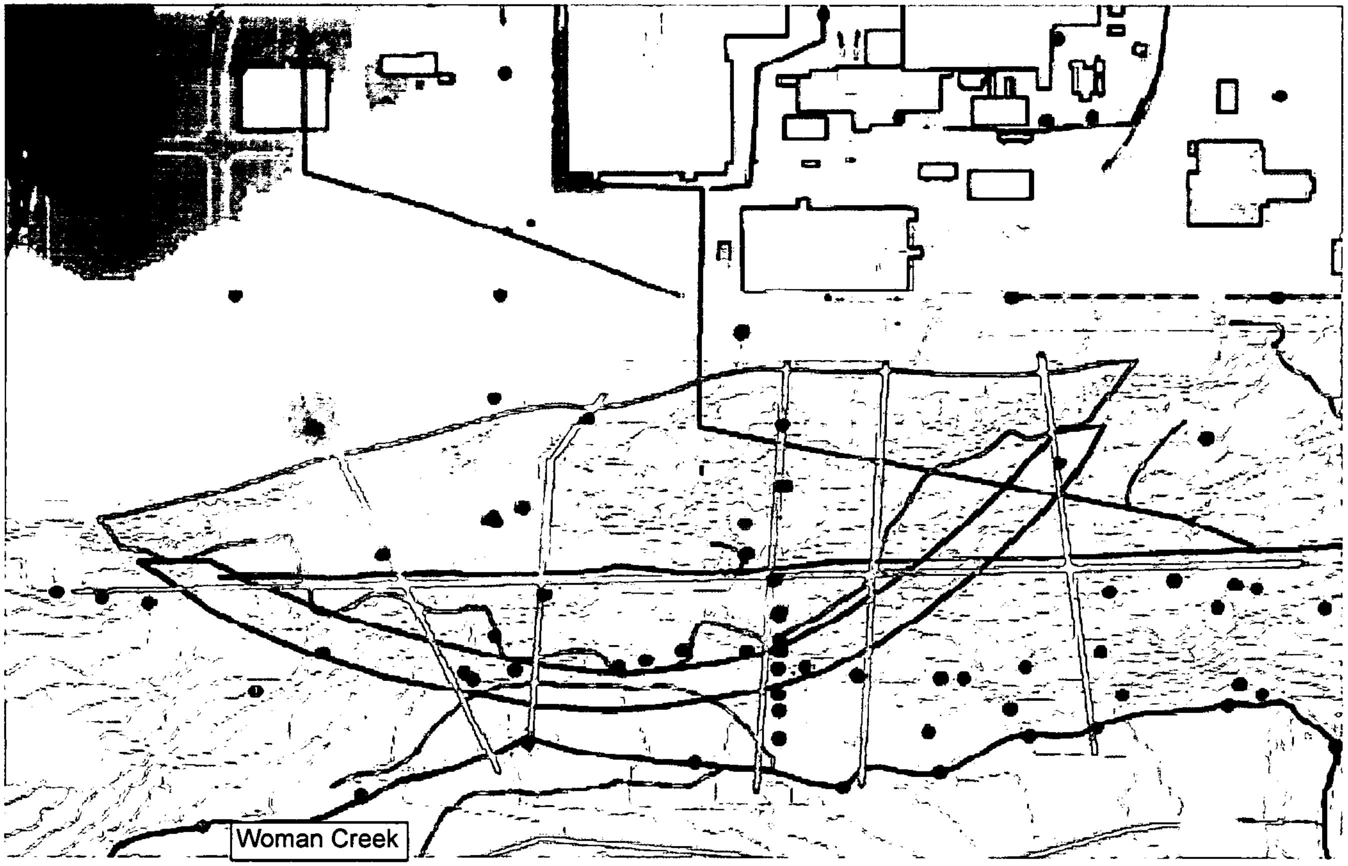

Simulated average annual groundwater height above weathered bedrock (feet).

	-15 - -10
	-10 - -5
	-5 - 0
	0 - 5
	5 - 10
	10 - 15
	15 - 20
	20 - 40
	No Data

Note:

1) Negative numbers indicate areas where groundwater levels are below weathered bedrock.

2) Positive numbers indicate saturated groundwater heights above the top of the weathered bedrock surface.

3) Scenario 1 assumes no modifications to the OLF.

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Figure 4-3a
Scenario 1 - Simulated (Typical Climate) average annual saturated height above Weathered Bedrock surface (ft).

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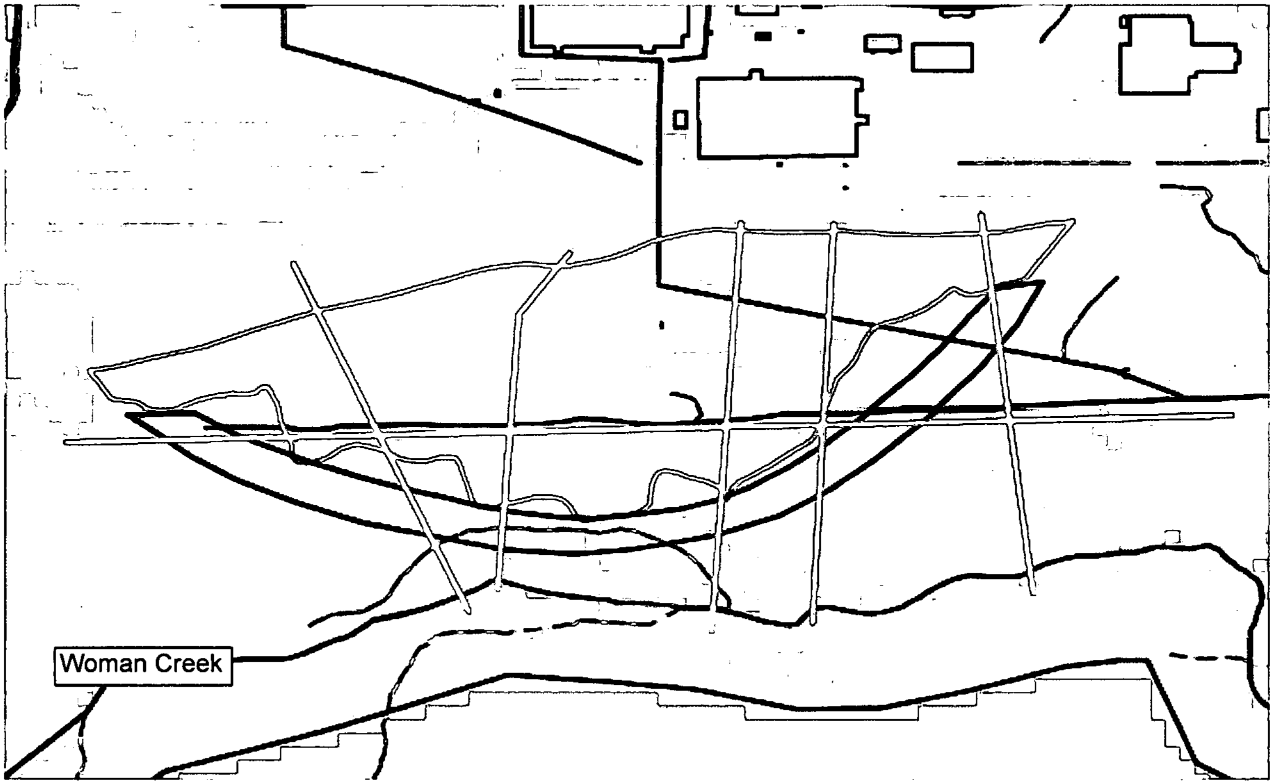

Change in groundwater levels (feet)

	-15 - -5
	-5 - -3
	-3 - -1
	-1 - 1
	1 - 3
	3 - 5
	5 - 15

Note:

1) Change in groundwater levels calculated by subtracting Scenario 1 simulated depths from current condition depths.

2) Negative numbers indicate areas where groundwater levels decrease from Calibration.

3) Positive numbers indicate saturated groundwater heights above the top of the weathered bedrock surface.

4) Change in levels south of Woman Creek invalid due to different model boundaries.

5) Scenario 1 assumes no modifications to the OLF.

Figure 4-3b
Scenario 1 change in groundwater levels (feet) from current conditions
(Effect of IA reconfiguration only)

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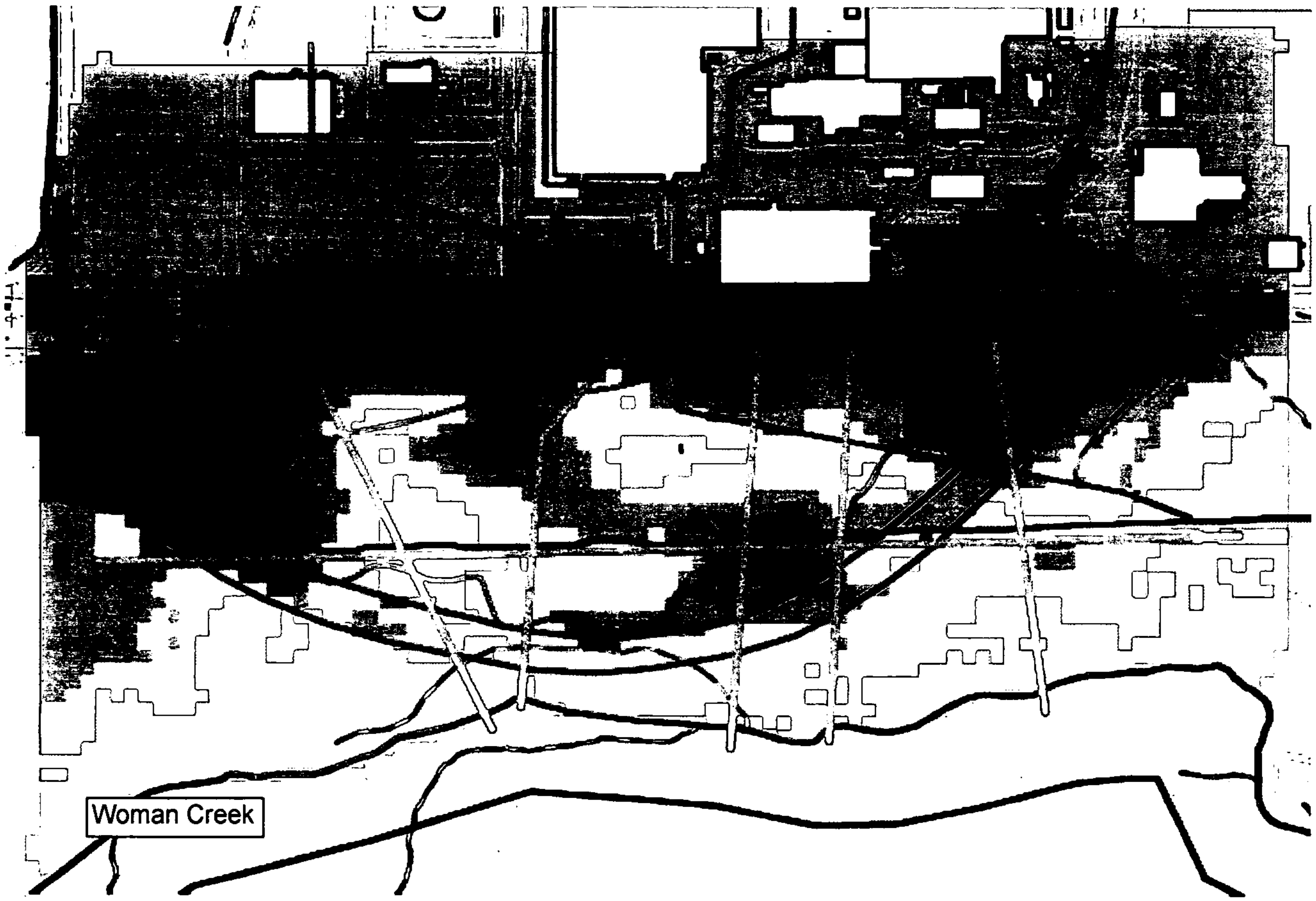

Simulated average annual groundwater depths (feet).

	-10 - 0
	0 - 5
	5 - 10
	10 - 15
	15 - 20
	20 - 45

Note:

1) Scenario 2 assumes IA closure and only a regrade over the OLF.

2) Negative numbers (yellow) indicate groundwater levels are above ground surface. These areas represent seeps.

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Figure 4-4
Scenario 2 - Simulated (Typical Climate) average annual groundwater depths (ft)

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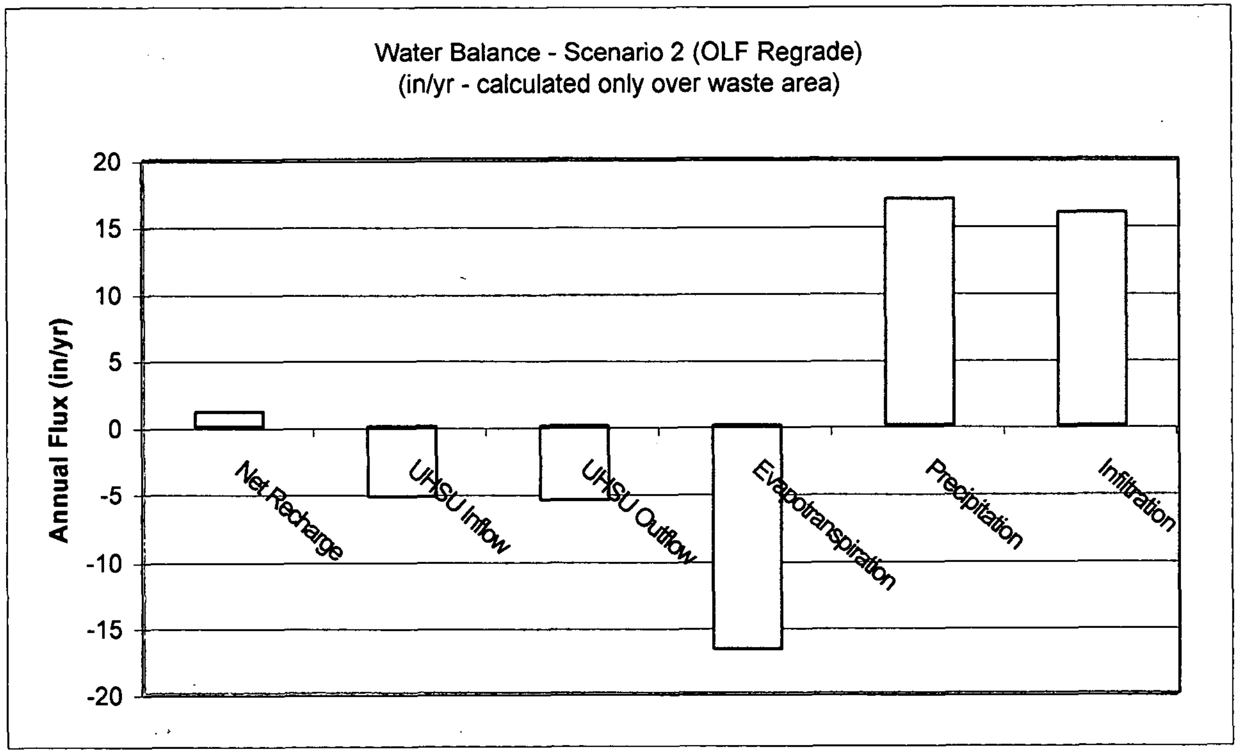

NOTE:
Infiltration differs from Net recharge because it is calculated as infiltration at ground surface only. Lateral UHSU inflow and outflows is calculated for waste, underlying colluvium, and weathered bedrock. Highest lateral flows are through the coluvium. Net recharge is calculated as net flux across water table and includes evapotranspiration loss through the unsaturated zone (Actual recharge is much higher).

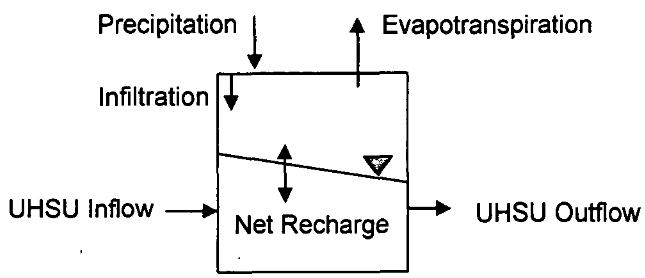

Figure 4-5
Scenario 2 -
Simulated water balance for waste area (in/yr)

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infiltrates due to relatively high surface soil permeabilities. Of this infiltration, most is lost via evapotranspiration through the root zone. A smaller, but important portion of this infiltration recharges the groundwater flow system. Although net annual recharge is less than annual lateral inflow or outflow (through the entire UHSU, including weathered bedrock and underlying Colluvium), it includes annual discharge to evapotranspiration via the unsaturated zone. Local recharge and evapotranspiration account for most of the groundwater level seasonal variability and changes in groundwater storage with time, rather than lateral flow variations.

In Figure 4-6 the average annual saturated height above weathered bedrock increases in the north-western part of the OLF and less notably in the east-central area (previously levels below top of bedrock) compared to Scenario 1.

As a conservative estimate of high water levels within the OLF area, a 100-year basis wet-year climate was simulated for Scenario 2. Results shown on Figure 4-7 indicate groundwater discharges to surface in the south-eastern and central areas of the OLF. This condition represents the wettest part of the wet-year climate sequence. Although not shown, it may also be possible for localized groundwater levels to reach ground surface in Scenario 2 during high recharge periods. For the wet climate, saturated heights above the weathered bedrock (Figure 4-8) increase above the typical climate, ranging from 5 to 15 feet over most of the OLF, but in localized areas it exceeds 20 feet. Average annual wet-year groundwater levels increase an average of about 1.3 feet over the waste area. Compared to average annual levels for a typical climate year, the highest wet-year levels increase from about 2 feet within the waste area to more than 4 feet south of the waste area.

Figure 4-9 illustrates changes in water table elevation from Scenario 1. Results indicate levels increase within most of the OLF 3 to 7 feet. This increase in elevation also appears to cause an increase north of the OLF in the B440/B444 area. Levels appear to decline up to 3 feet immediately south of the waste extent.

4.2.3 Scenario 3 – OLF Regrade, Buttress fill, and Buttress drain

A buttress fill and upgradient buttress drain are simulated in Scenario 3 at the southern end of the waste area (see Figure 3-1). The buttress fill is assumed to extend to the top of the weathered bedrock and is assigned a very low hydraulic conductivity (1e-10 m/s). It is represented in the model as using cells wide as indicated by the boundary shown on Figure 3-1. The buttress drain is also assumed to extent to the top of the weathered bedrock. In the model, a low resistance drain is simulated by assigning a high conductance to the drain cells.

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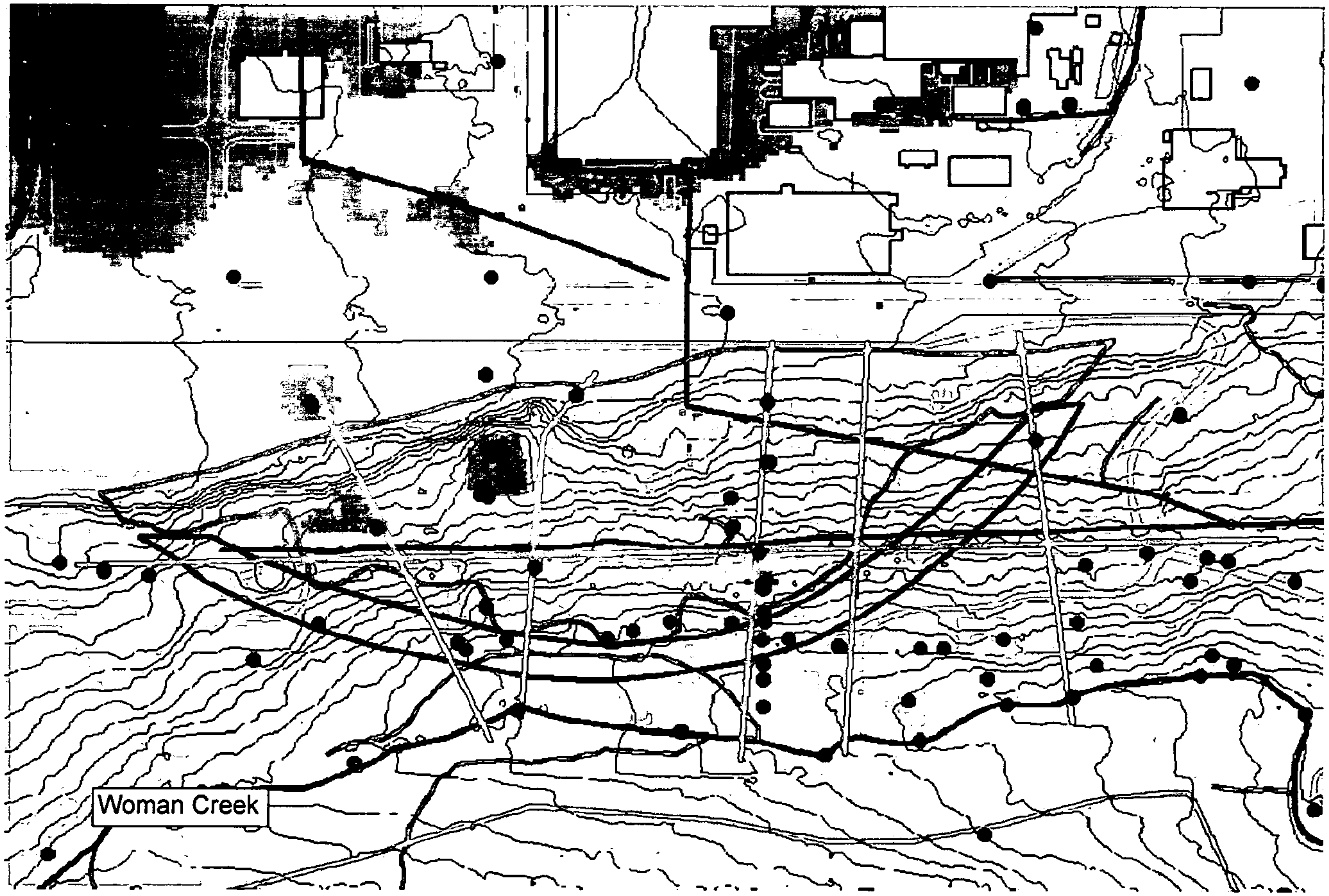

Simulated average annual groundwater height above weathered bedrock (feet).

	-15 - -10
	-10 - -5
	-5 - 0
	0 - 5
	5 - 10
	10 - 15
	15 - 20
	20 - 40
	No Data

Note:

1) Scenario 2 assumes the OLF is regraded along with the IA. No other modifications in the OLF assumed.

2) Negative numbers indicate areas where groundwater levels are below weathered bedrock.

3) Positive numbers indicate saturated groundwater heights above the top of the weathered bedrock surface.

Figure 4-6

Scenario 2 - Simulated (Typical Climate) average annual saturated height above Weathered Bedrock surface (ft)

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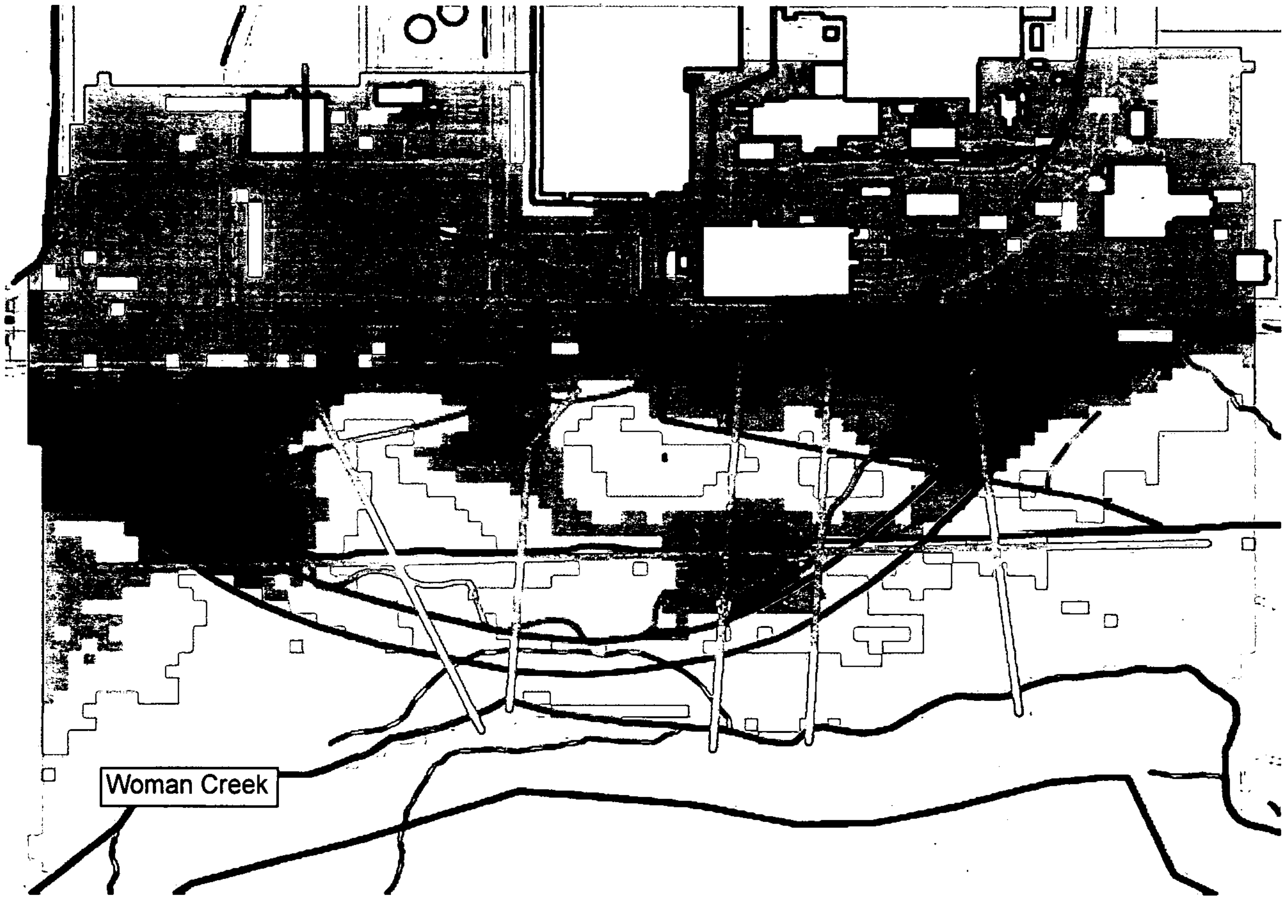

Simulated average annual groundwater depths (feet).

	-10 - 0
	0 - 5
	5 - 10
	10 - 15
	15 - 20
	20 - 45

Note:
1) Negative numbers (yellow) indicate groundwater levels are above ground surface. These areas represent seeps.

2) Scenario 2 assumes OLF regrade only.

Figure 4-7
Scenario 2 - Simulated (Wet-Year Climate) minimum annual groundwater depths (ft)

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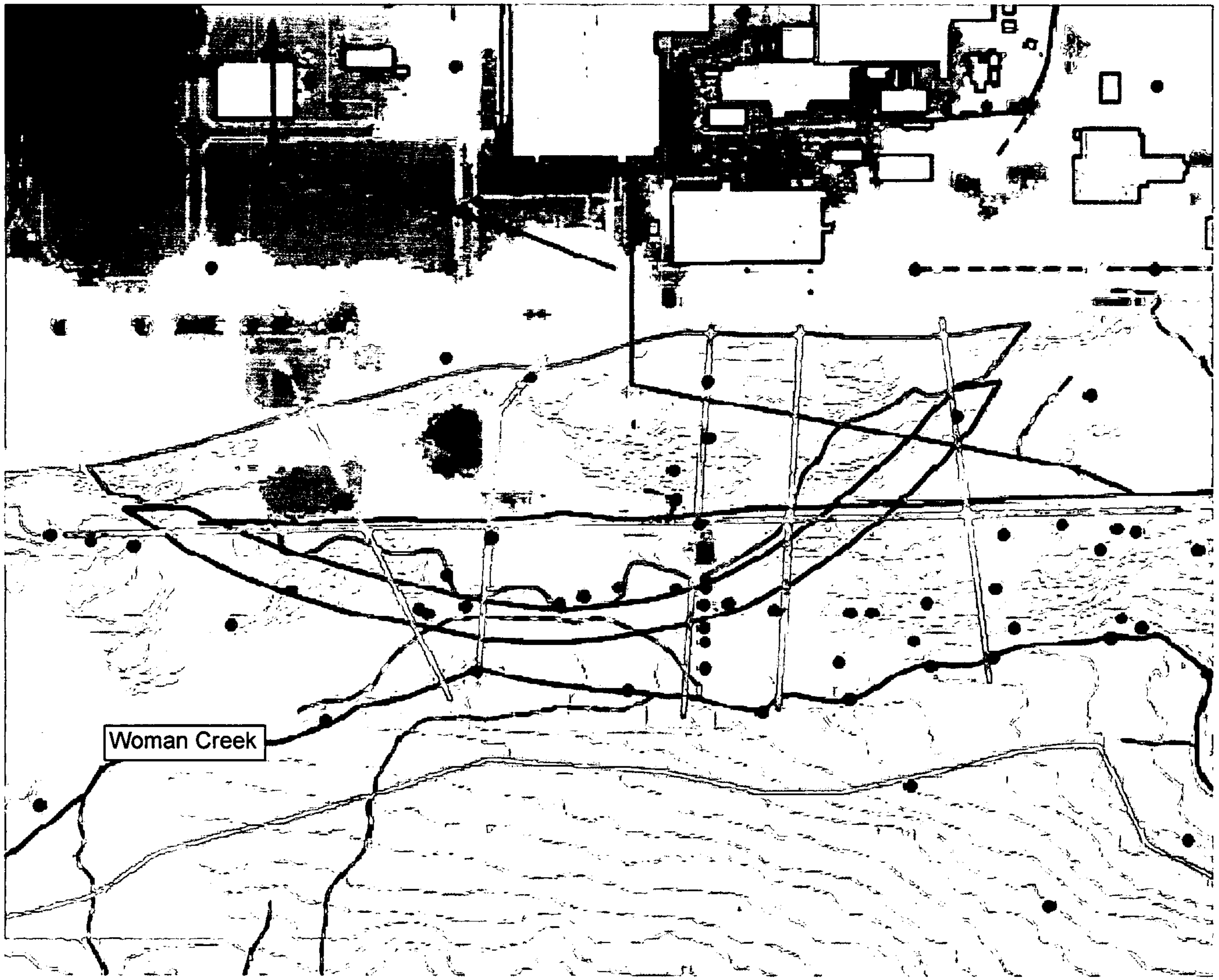

Simulated average annual groundwater height above weathered bedrock (feet).

	-15 - -10
	-10 - -5
	-5 - 0
	0 - 5
	5 - 10
	10 - 15
	15 - 20
	20 - 40
	No Data

Note:

1) Negative numbers indicate areas where groundwater levels are below weathered bedrock.

2) Positive numbers indicate saturated groundwater heights above the top of the weathered bedrock surface.

3) Scenario 2 assumes OLF regrade only.

Figure 4-8

Scenario 2 - Simulated (Wet-Year Climate) maximum annual saturated height above Weathered Bedrock surface (ft)

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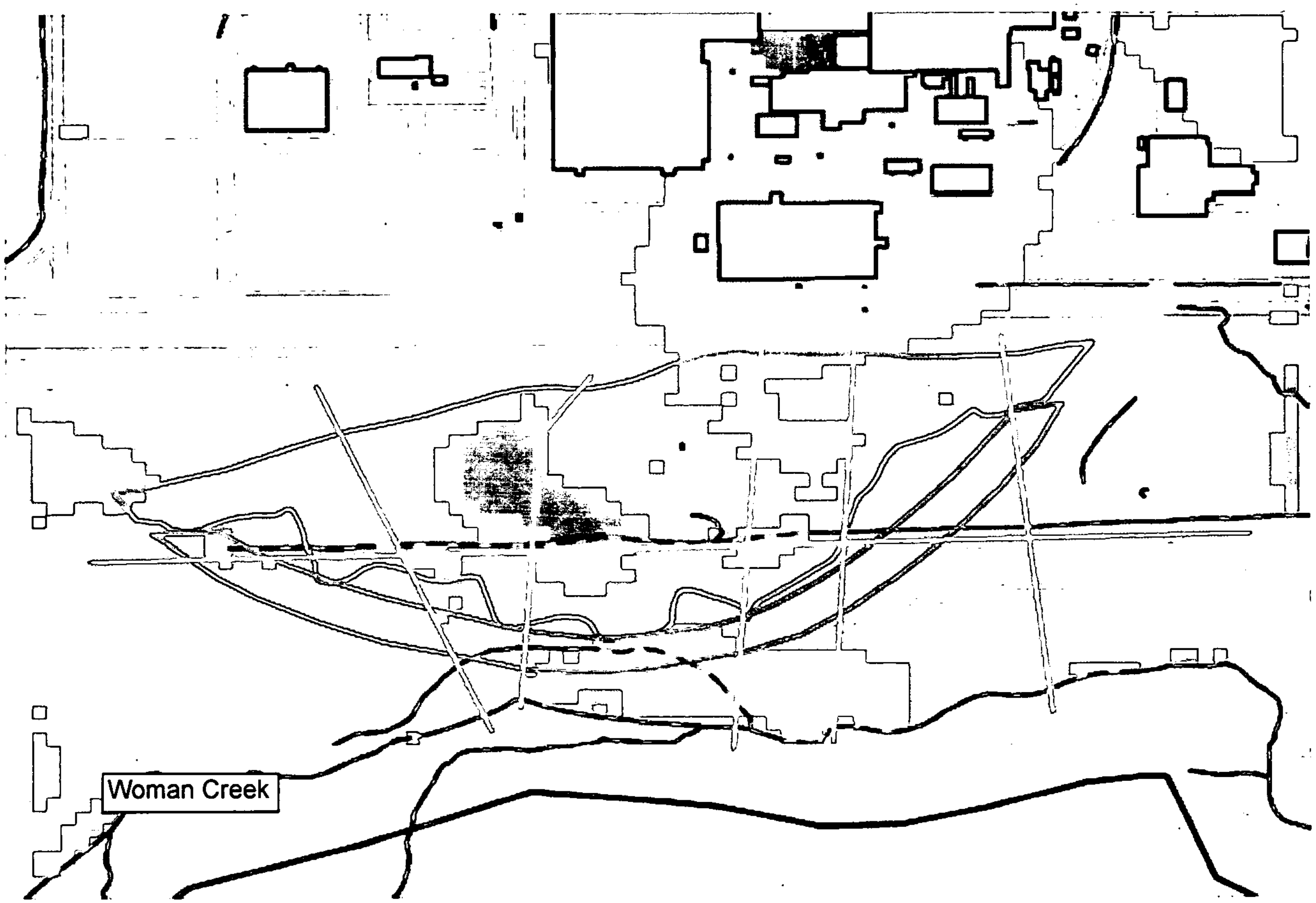

Change in groundwater levels (feet)

- -15 - -5
- -5 - -3
- -3 - -1
- -1 - 1
- 1 - 3
- 3 - 5
- 5 - 15

Note:

1) Change in groundwater levels calculated by subtracting Scenario 1 depths from Scenario 2.

2) Negative numbers indicate areas where groundwater levels decrease from Scenario 1.

3) Positive numbers indicate saturated groundwater heights above the top of the weathered bedrock surface.

4) Scenario 2 assumes OLF regrade only.

Figure 4-9
Scenario 2 change in groundwater levels (ft) from Scenario 1
(Effect of regrade only - Typical climate sequence)

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Simulated groundwater depths and saturated heights above the weathered bedrock (Figures 4-10 and 4-11, respectively) are similar those generated in Scenario 2, but decline due to the buttress drain upgradient of the buttress fill. Compared to Scenario 2, levels decrease up to about 3 feet for the lower half of the OLF extent and decrease up to about 7 feet near the buttress drain upgradient of the buttress, as shown on Figure 4-12.

4.2.4 Scenario 4 – OLF Regrade, Buttress fill, Buttress drain, and Slurry Wall

The effect of adding a slurry wall to the last scenario with a regrade, buttress fill and buttress drain is described here. The slurry wall, placed immediately north of the waste extent in the integrated model, is assigned a very low hydraulic conductivity (1e-10 m/s), similar to the buttress fill. The water balance performed on Scenario 2 indicates that most of the lateral inflow occurs in the unconsolidated material of the UHSU. Therefore, extending the slurry wall from ground surface to the top of the weathered bedrock will block most of the lateral inflow to the OLF from upgradient.

Simulated average annual groundwater depths, shown on Figure 4-13 are similar to Scenario 3. Only a slight adjustment to the average annual saturated height above the weathered bedrock is simulated (Figure 4-14). This is further indicated on Figure 4-15, showing the change in groundwater levels compared to Scenario 3. Results show that levels immediately upgradient of the slurry wall increase less than 3 feet, while those immediately downgradient, within the waste area, decrease less than 3 feet. The change in levels is constrained to about 200 to 300 feet on either side of the slurry wall. Based on this simulation and the lower weathered bedrock permeabilities, additional declines in the water table are unlikely if the slurry wall were extended through the weathered bedrock.

5.0 Fate and Transport of VOCs in the OLF area

5.1 Model Development

The fate and transport of VOCs detected in the OLF area are evaluated for closure Scenarios 2 and 3. These two scenarios are selected for fate and transport simulations because they represent configurations with the greatest potential for producing higher downgradient VOC concentrations. Specifically, impacts to surface water (Woman Creek, or seeps) are assessed. Available groundwater sampling data indicate elevated concentrations of Tetrachloroethylene (PCE) were detected in the central portion of the OLF waste area.

The approach used to model the fate and transport of PCE (and its daughter products) from the waste area is consistent with that described in detail in the IA VOC fate and transport modeling study (KH, 2004). The RT3D code is used to

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Simulated average annual groundwater depths (feet).

	-10 - 0
	0 - 5
	5 - 10
	10 - 15
	15 - 20
	20 - 45

Note:

1) Scenario 3 assumes OLF regrade, clay buttress and toe drain on upgradient side of buttress.

2) Negative numbers (yellow) indicate groundwater levels are above ground surface. These areas represent seeps.

3) Scenario 3 includes OLF regrade, Buttress fill and drain.

Figure 4-10
Scenario 3 – Simulated (Typical Climate) average annual groundwater depths (ft)

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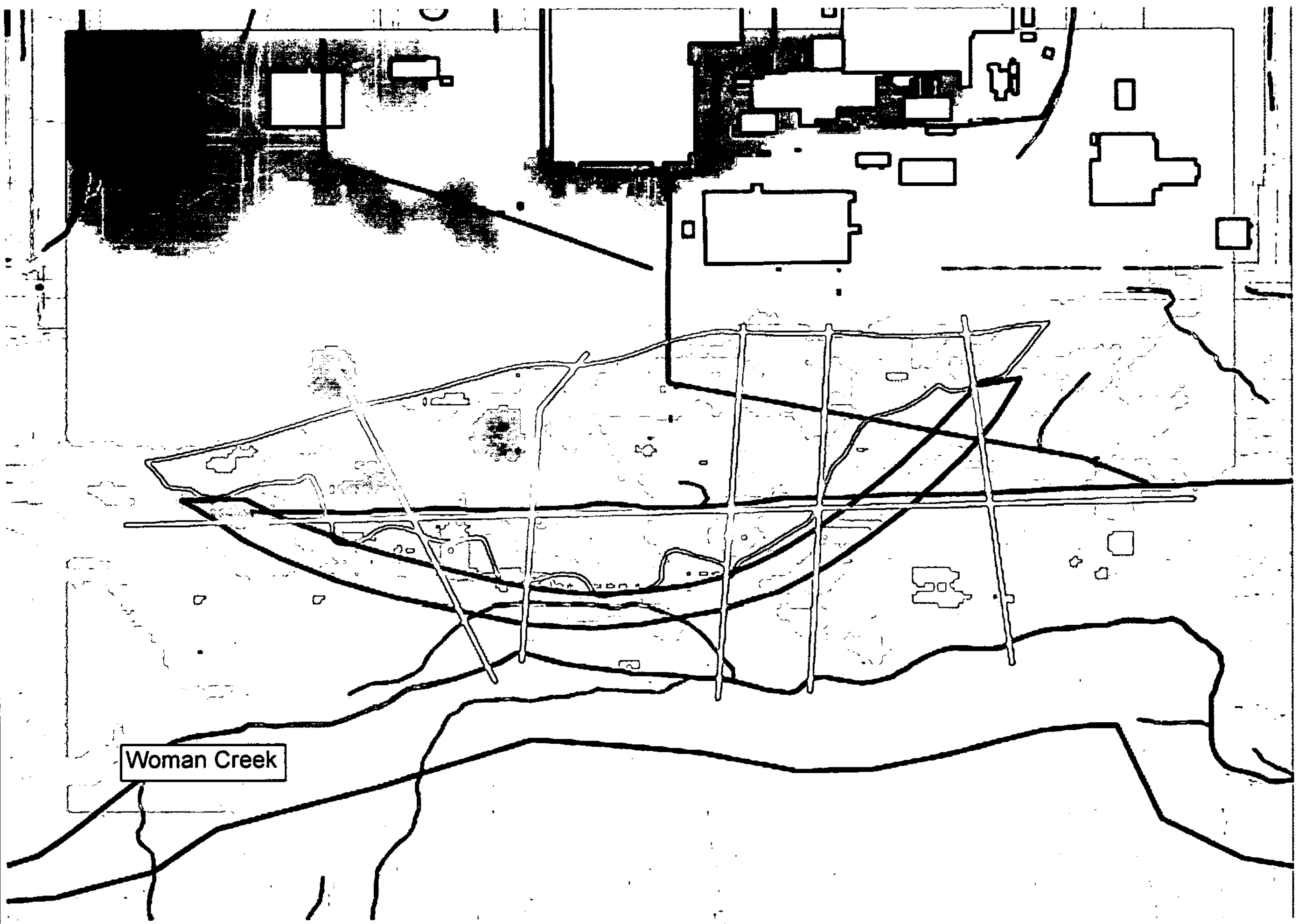

Simulated average annual groundwater height above weathered bedrock (feet).

	-15 - -10
	-10 - -5
	-5 - 0
	0 - 5
	5 - 10
	10 - 15
	15 - 20
	20 - 40
	No Data

Note:
1) Negative numbers indicate areas where groundwater levels are below weathered bedrock.

2) Positive numbers indicate saturated groundwater heights above the top of the weathered bedrock surface.

3) Scenario 3 includes OLF regrade, Buttress fill and drain.

Figure 4-11
Scenario 3 – Simulated (Typical Climate) average annual saturated height above Weathered Bedrock surface (ft).

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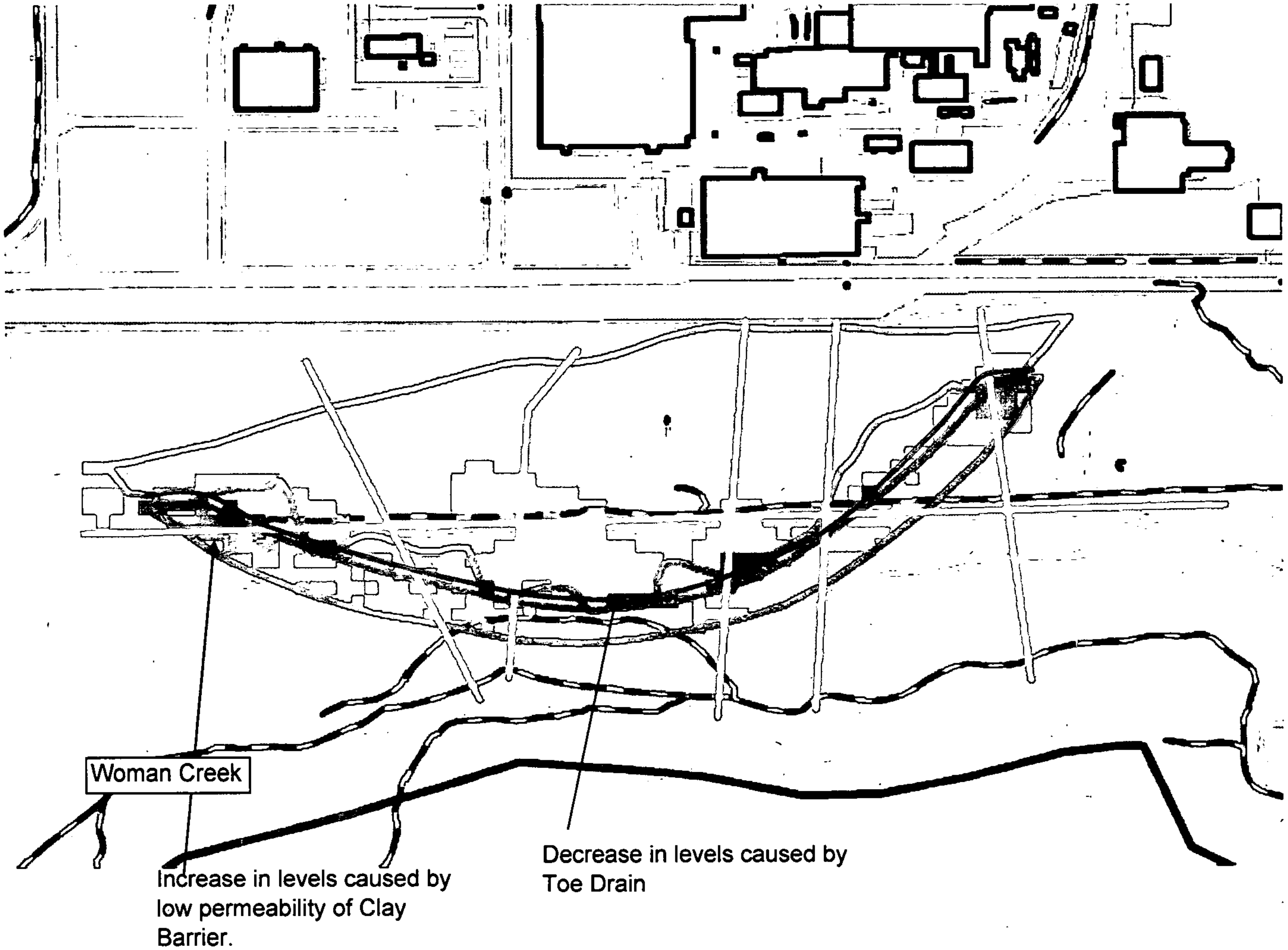

Change in groundwater levels (feet)

- -4 - -3
- -3 - -2
- -2 - -1
- -1 - -0.1
- -0.1 - 0.1
- 0.1 - 1
- 1 - 2
- 2 - 3
- 3 - 4
- 4 - 10

Note:

1) Change in groundwater levels calculated by subtracting Scenario 2 depths from Scenario 3.

2) Negative numbers indicate areas where groundwater levels decrease from Scenario 2.

3) Positive numbers indicate saturated groundwater heights above the top of the weathered bedrock surface.

4) Scenario 3 includes OLF regrade, Buttress fill and drain.

Figure 4-12
Scenario 3 change in groundwater levels (feet) from Scenario 2
(Effect of adding clay buttress and toe drain to regrade)

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Simulated average annual groundwater depths (feet).

	-10 - 0
	0 - 5
	5 - 10
	10 - 15
	15 - 20
	20 - 45

Note:

1) Scenario 4 assumes OLF regrade, clay buttress, toe drain on upgradient side of buttress, and slurry wall (see Figure 3-1 for locations of these features).

2) Negative numbers (yellow) indicate groundwater levels are above ground surface. These areas represent seeps.

3) Scenario 4 includes OLF regrade, Buttress fill, drain and upgradient slurry wall.

Figure 4-13
Scenario 4 – Simulated (Typical Climate) average annual groundwater depths (ft)

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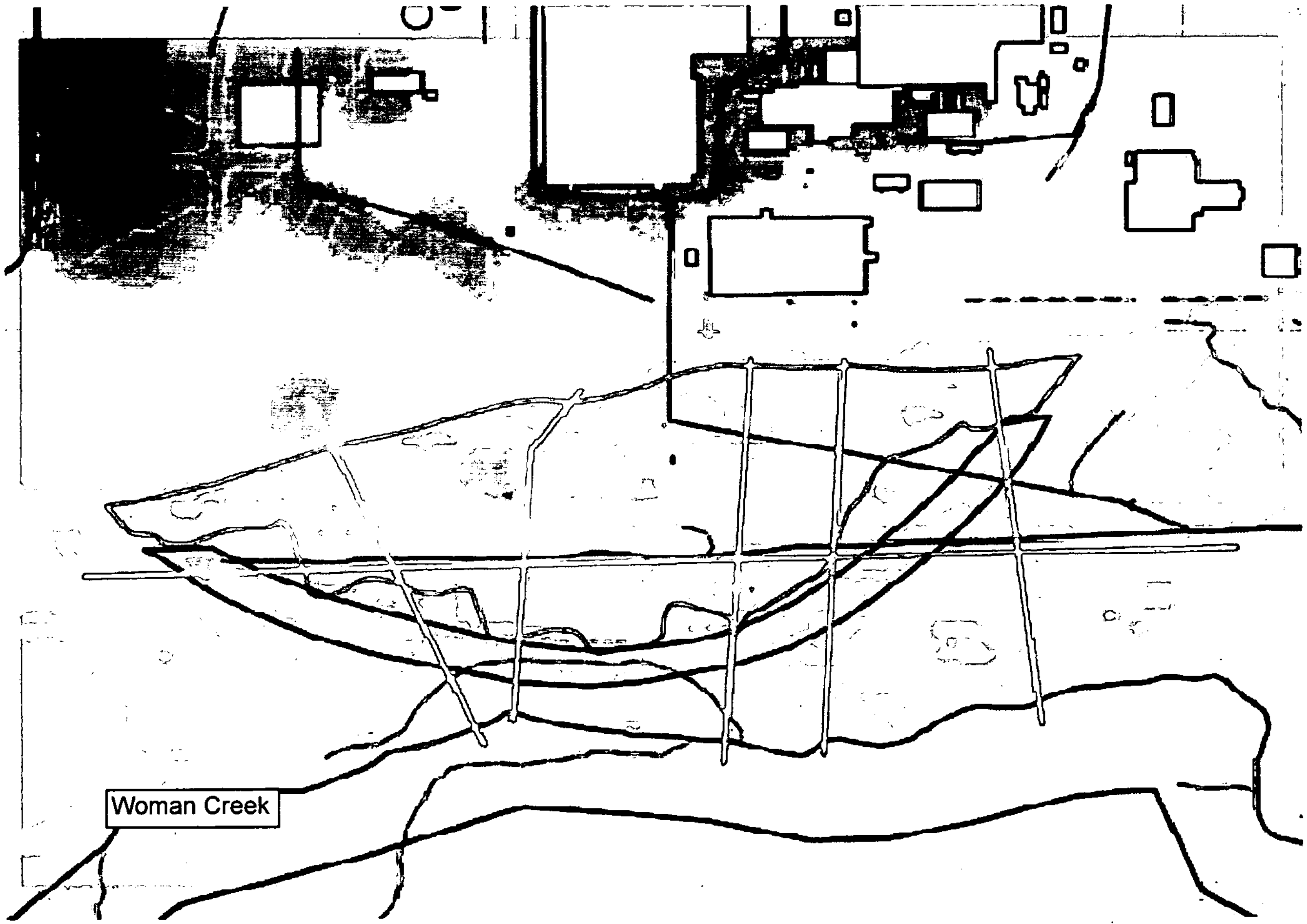

Simulated average annual groundwater height above weathered bedrock (feet).

	-15 - -10
	-10 - -5
	-5 - 0
	0 - 5
	5 - 10
	10 - 15
	15 - 20
	20 - 40
	No Data

Note:

1) Negative numbers indicate areas where groundwater levels are below weathered bedrock.

2) Positive numbers indicate saturated groundwater heights above the top of the weathered bedrock surface.

3) Scenario 4 includes OLF regrade, Buttress fill, drain and upgradient slurry wall.

Figure 4-14

Scenario 4 – Simulated (Typical Climate) average annual saturated height above Weathered Bedrock surface (ft).

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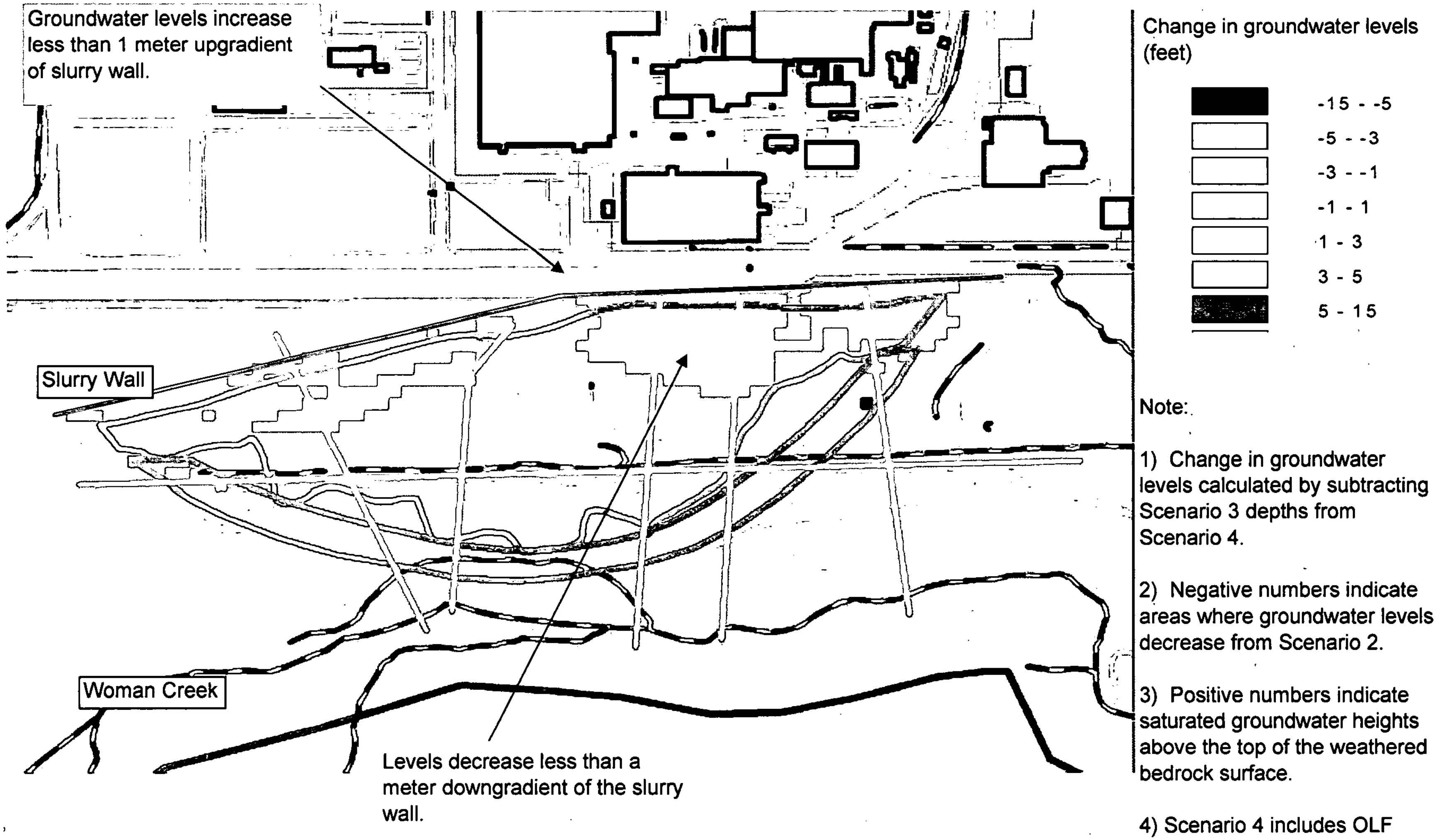

Note:

1) Change in groundwater levels calculated by subtracting Scenario 3 depths from Scenario 4.

2) Negative numbers indicate areas where groundwater levels decrease from Scenario 2.

3) Positive numbers indicate saturated groundwater heights above the top of the weathered bedrock surface.

4) Scenario 4 includes OLF regrade, Buttress fill, drain and upgradient slurry wall.

Figure 4-15
Scenario 4 change in groundwater levels (feet) from Scenario 3
(Effect of adding a slurry wall)

model the fate and transport of PCE so that advection and attenuation processes including degradation, sorption, diffusion and dispersion could be considered.

Three-dimensional time-averaged water levels (WY2000), estimated using the integrated flow model for Scenarios 2 and 3, are first used to define approximate steady-state velocity fields for the RT3D simulations. A number of conservative fate and transport simulations are then conducted to estimate a range of long-term groundwater concentrations at surface water discharge locations given uncertainties in source location, depth and timing, among other parameters controlling fate/transport. Source locations simulated in the model are based on inferred locations (shown on Figure 5-1) and long-term concentrations are assumed constant. This assumption is reasonable because concentrations at wells in the OLF show no clear increasing, or decreasing trends in time.

The following long-term simulations were conducted for Scenarios 2 and 3:

- Scenario 1 - Basecase;
- Scenario 2 - Low degradation (one tenth of basecase);
- Scenario 3 - Low porosity (halved for all layers);
- Scenario 4 - Low degradation and increase in hydraulic conductivity (one tenth and three times for all layers, respectively);
- Scenario 5 - Advection-dispersion only (no sorption, degradation, or ET loss), increase in hydraulic conductivity (2 times all layers); and
- Scenario 6 - Advection=dispersion only.
- Fate and Transport Simulation Results

Results from both simulations show that neither PCE, nor its daughter products, reach Woman Creek at concentrations above surface water action concentrations for any of the conservative simulations considered. Results are summarized on Figures 5-2 and 5-3, for scenarios 2 and 3, respectively. For scenario 3, with the buttress fill and buttress drain, more conservative simulations indicate it is possible for concentrations to reach the drain, but they are likely to be lower than the surface water action levels.

6.0 Summary and Conclusions

This summary presents modeling the integrated hydrologic response of current conditions and four different OLF closure configuration scenarios, and the fate and transport from inferred source areas. Several steps were required. First, all available data, including recent water levels and geotechnical information, were compiled into a GIS and analyzed. A localized, fully-integrated flow model was then developed for the OLF area based on these data for current conditions. Model performance runs were simulated to demonstrate that parameter values were appropriate for simulating closure configurations. Next, the integrated model was modified to simulate the four closure configurations to show the

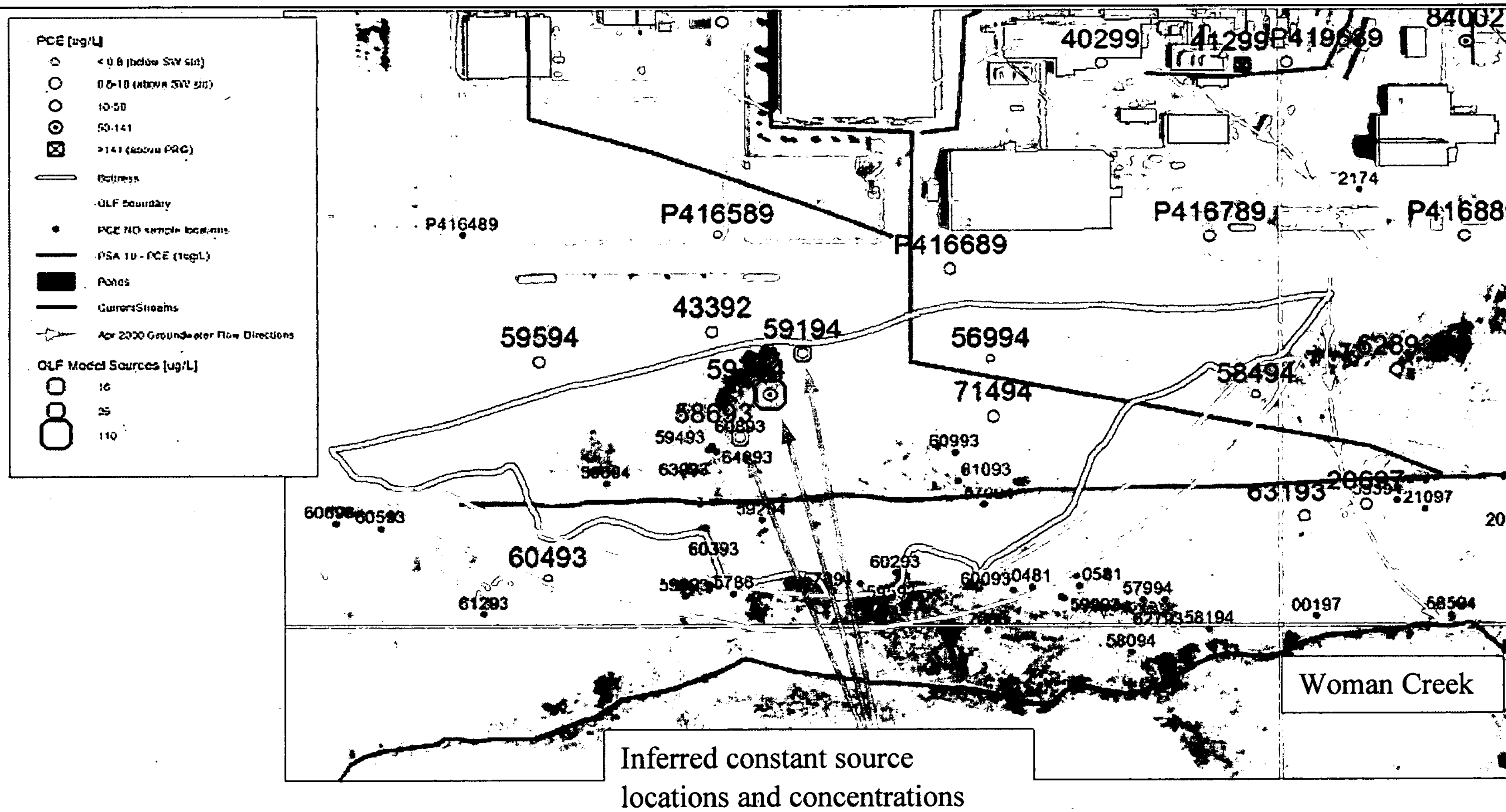

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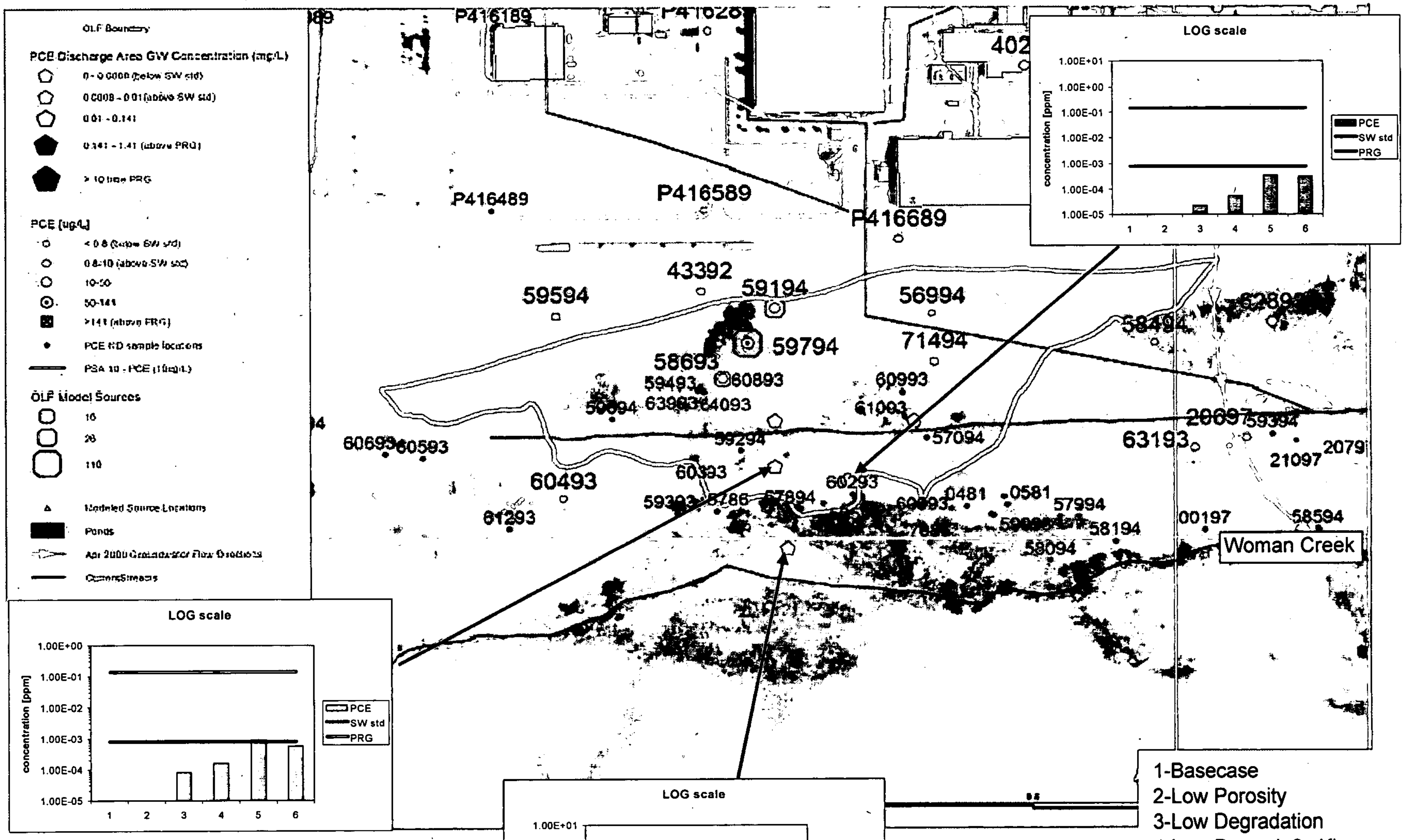
Figure 5-1
Inferred location of VOC sources in the OLF area



Note: Results from all scenarios (conservative parameter values) show that long-term concentrations upgradient of Woman Creek are less than surface water standards (blue line on graphs).

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Figure 5-2
Fate and Transport Results – Scenario 2

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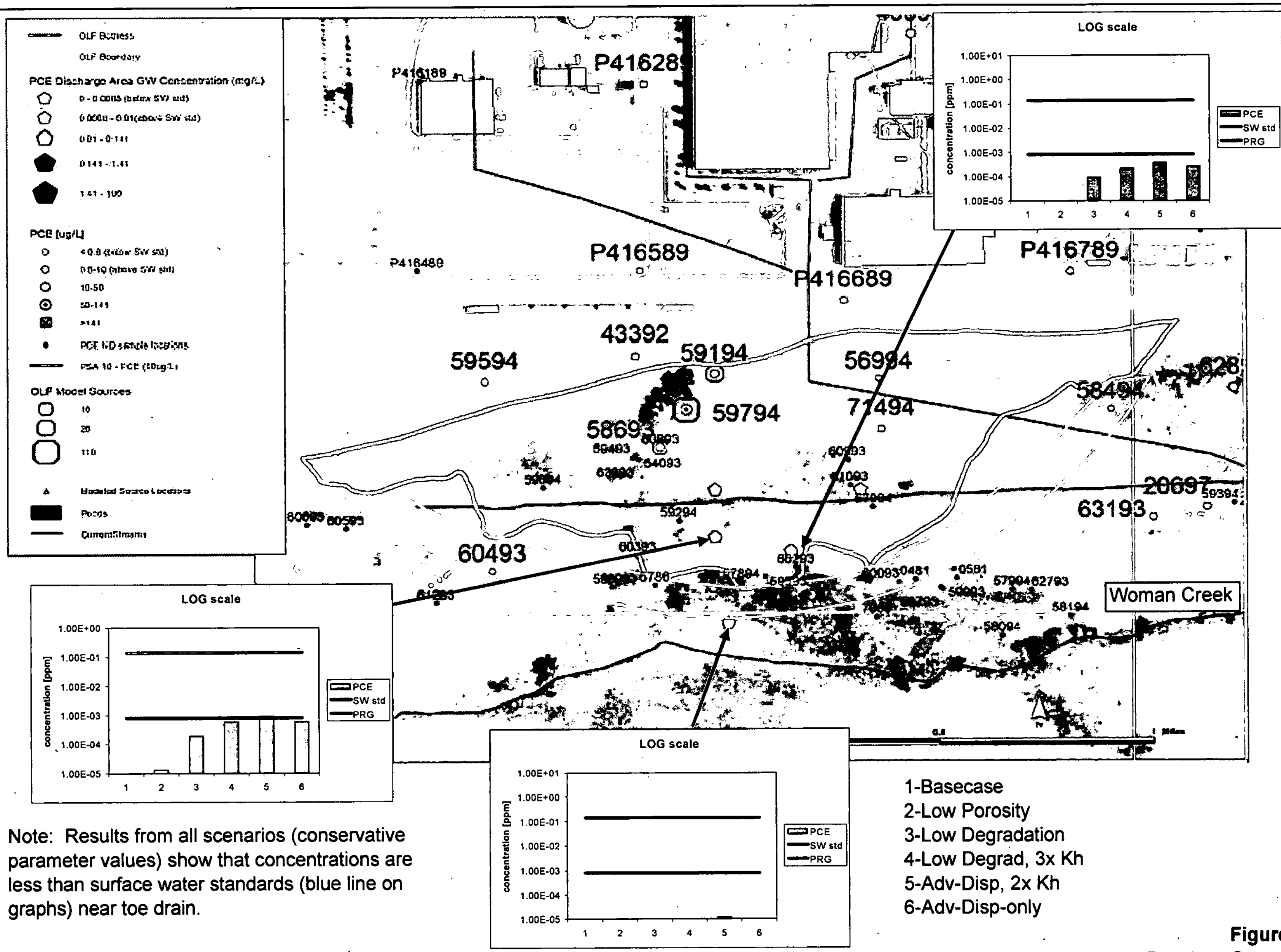

1-Basecase
2-Low Porosity
3-Low Degradation
4-Low Degrad, 3x Kh
5-Adv-Disp, 2x Kh
6-Adv-Disp-only

Note: Results from all scenarios (conservative parameter values) show that concentrations are less than surface water standards (blue line on graphs) near toe drain.

Figure 5-3
Fate and Transport Results – Scenario 3

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relative effects of each scenario. A 100-year wet-climate sequence was simulated in the basecase, OLF regrade scenario to approximate the highest groundwater levels in the OLF area. Finally, the fate and transport of elevated levels of PCE within the OLF was evaluated using the reactive transport code, RT3D, for two closure configurations.

The four OLF closure configurations considered in the integrated flow model include the following:

- Scenario 1 - IA reconfiguration, no OLF modifications;
- Scenario 2 - IA reconfiguration, OLF regrade (basecase);
- Scenario 3 - IA reconfiguration, OLF regrade, buttress fill, and buttress drain; and
- Scenario 4 - IA reconfiguration, OLF regrade, buttress fill, buttress drain, and slurry wall.

Several conclusions can be made from the integrated OLF flow model simulations and VOC fate and transport modeling. These are summarized below:

1) A combination of natural and anthropogenic factors affects local groundwater levels within the OLF area in the current (pre-closure) configuration. These include the following:
    1) Anthropogenic factors:
        1) Drains north of OLF in IA;
        2) Utility corridors in IA;
        3) Leaky water supply lines (Bldg 124 area); and
        4) Pavement and buildings.
    2) Natural factors:
        1) Hillslope configuration:
            1) Weathered bedrock surface;
            2) Unconsolidated thickness spatial distribution; and
            3) Vegetation distribution/types.
        2) Climate sequence characteristics; and
        3) Unsaturated and saturated zone hydraulic properties of waste and surrounding media.
2) Historical time-average groundwater levels in the OLF area indicate saturated heights above the weathered bedrock range from 0 to 10 feet over about two thirds of the waste extent, while the levels are actually below the bedrock over the remaining one third.
3) For current conditions, average annual observed groundwater depths throughout the OLF area vary from over 20 feet depth at the top of the

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hillslope to less than 3 feet near Woman Creek and in shallow bedrock areas within the OLF.

4) Model results show that reconfiguring the IA (Scenario 1) causes groundwater levels to increase less than one foot over the OLF. However locally, levels decrease less than 3 feet and increase up to 4 feet. Simulated depths are similar to current conditions and range from less than 5 feet to over 20 feet within the OLF.

5) Simulated effects of regrading the OLF and reconfiguring the IA (Scenario 2) for a typical climate sequence (WY2000) cause levels to increase an average of about two feet. Locally they decrease up to 3.5 feet and increase up to nearly 7 feet. Simulated groundwater depths vary throughout the OLF, mostly in response to 'fill' and 'cut' adjustments. At the western and eastern waste extents depths increase to near 40 feet due to increased fill thickness. Saturated heights above the bedrock increase from 3 to 7 feet over most of the OLF compared to Scenario 1.

6) Simulating a wet-year climate (100-year basis) sequence for Scenario 2 causes average OLF groundwater levels to increase about two feet (ranging from 0 to 4 feet) compared to a typical climate sequence. Results also indicate that groundwater reaches ground surface in shallow bedrock areas, though this could be controlled by increasing the regrade surface height above bedrock. These simulated groundwater levels represent conservatively high levels that might be sustained for up to a month during a wet year climate sequence.

7) Simulated effects of adding a buttress fill and upgradient buttress drain (Scenario 3) cause average annual groundwater levels to decrease less than one foot over the OLF. However locally, the drain causes levels to decrease up to 3 feet over the southern half of the OLF. Levels near the drain decrease about 11 feet. Simulated annual discharge rates from the drain are less than 1 gpm.

8) Simulated effects of adding a slurry wall to Scenario 3 (Scenario 4) cause average annual groundwater levels over the OLF to change less than one foot. However levels downgradient (south) of the slurry wall decrease less than 3 feet, while those upgradient of the slurry wall (north) increase up to 3 feet within about 300 feet.

9) Results of the current and closure simulations conducted in this study indicate that surface regrading results in the largest impact on OLF groundwater levels. Modeling also shows that seeps may occur under wetter climate though this could be controlled by adjusting the surface regrade topography.

10) Reactive fate and transport modeling of PCE (and daughter products) detected in groundwater in the OLF waste indicate that concentrations at

Woman Creek remain well below surface water standards for both Scenario 1 and 3. More conservative fate and transport scenarios (most conservative parameter values) show that groundwater concentrations may reach the buttress drain at detectable concentrations, though they remain below the surface water standards. Results of the fate and transport simulations assume that the PCE source concentrations remain constant during any regrade of the area.

11) A sensitivity analysis to determine the most sensitive parameters controlling water levels in the OLF was not conducted in this study, though results suggest that the regrade surface, bedrock depth and waste area hydraulic properties are the most sensitive. An uncertainty analysis to assess the range of hydrologic response to input parameter value uncertainty was also not conducted in this study. As such, simulated responses could change depending on the specific parameter values used, though reasonable values were assumed.

7.0 References

Kaiser-Hill (KH). 2002. Site-Wide Water Balance Model Report for the Rocky Flats Environmental Technology Site. May.

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